# ELECTRIC CONTROL GEAR

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# ELECTRIC CONTROL GEAR AND INDUSTRIAL ELECTRIFICATION

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# PREFACE

THE extensive use that is being made of electricity for driving almost everything of importance in the industrial world is interesting a wider and wider circle of technical workers as time goes on. Such an interest involves an acquaintance not only with electric motors, but also with electrical control gear, which is the factor responsible for the more remarkable developments and the more significant advances of the past fifteen or twenty years. The time seemed opportune, therefore, for the publication of a book which should deal especially with this branch of electrical work in its modern aspects; and should include a description of the control apparatus itself, the need which has called the various items into existence, and the measure of success with which the need has been fulfilled.

In venturing to compile such a volume, the author has been encouraged by a realization of the many classes of engineer who may be glad to have information on this subject; and he has endeavoured to supply the wants of as many of these as possible. The student has been particularly kept in mind when the subject in general, and certain specialized sections, are being entered upon, brief introductory portions having been included with the object of enabling the learner to read continuously without frequent reference to preliminary text-books. For the designer and manufacturer, data and constructional information derived from intimate practical experience have been included whenever the opportunity presented itself. For the consultant and user, full information has been given of the characteristics and applicability of the various pieces of apparatus; and special attention has been devoted to the building-up of a control scheme and the reading of a complicated diagram. The requirements of the lecturer have been consulted by the detailed description of the illustrations and by their careful composition and selection; among other considerations, their nature and shape have been made as suitable for lantern projection as practicable.

The selection of a title that shall indicate the full scope of the book has not been an easy matter; for the treatment of such a subject must be a comprehensive one. Not only must the characteristics of the

electric motor be understood in order that the accessory equipment may be correctly prescribed, but it is impossible to specify either motor or control gear until the load which is to be operated has been studied. Information has therefore been included on both these heads; and if brevity were not an essential virtue the title might have been amplified accordingly.

It has nevertheless been borne in mind that the book is primarily concerned with the design, arrangement, and construction of the controlling apparatus, and this section has been treated in full detail. In doing so, the author has adopted the plan of dealing first with the individual items, special attention being bestowed upon the contactor and its auxiliaries, as the most notable components of modern automatic electric equipment. The association and combination of these to form complete schemes having any desired characteristics are then discussed; and this section is followed by the description of typical installations in the principal departments of industrial work. The main course has been introduced by two chapters on D.C. and A.C. motors, recapitulating the fundamental principles which have a bearing upon control gear design; and the later chapters dealing with its application are each prefaced with a brief consideration of the nature and requirements of the particular mechanical load which is to be driven.

The chief problem in formulating a design is to provide a direct response to every individual requirement of the case under treatment. It is the author's conviction that these requirements are the more surely and fully ascertained by reasoning as far as possible from first principles. Such a method may be thought by some to include elementary matter that should be somewhat beneath the notice of the advanced worker. It is just these fundamentals, however, that are apt to dictate the design of even the most elaborate piece of apparatus, and that are liable to be lost sight of by one who has passed far beyond the elementary stage of the subject; and the author has therefore followed this line in the present volume, notably in Chaps. II and III. Care has, however, been taken to introduce no theory, fundamental or otherwise, that is not relevant to the main purpose of the book.

It is realized that many readers do not desire to read a technical work right through from cover to cover, but prefer one which can be used for purposes of reference. The policy has therefore been followed of making each chapter as far as possible complete in itself, and capable of being read and understood independently of those that come before and after. Such references as are made to other parts of the book are

mainly to illustrations, in order to utilize the graphical possibilities of these to the full.

In practically every case the diagrams have been specially drawn for this volume, the object being to make them easily intelligible to readers of the particular section in which each occurs. Few plans of connexions can appear so utterly bewildering to a learner as a contactor diagram; and considerable thought has been given to the method of introducing these in order to assist such readers.

First, uniform symbols have been adopted throughout, these conforming with the well-recognized British Standards tabulated in B.S.S. 108. Secondly, the main and auxiliary circuits have been kept as distinct as possible by the employment of different kinds of lines for each. Thirdly, the various sections of each scheme have been segregated to the utmost that could be achieved. Fourthly, no more complexity has been introduced at any place than is necessary to illustrate the text. Where such details as the line switches and fuses, operating coils, or even the whole auxiliary circuit, are not needed, they have been omitted and a note added to this effect. Fifthly, the elaboration of the schemes is graded, those occurring early showing only the fundamental components, and the accessories being added as the discussion proceeds. Finally, no attempt has been made to represent the actual location of the parts on the panel until the reader has become familiarized with their electrical relationships one with the other. It is hoped that the above procedure will materially reduce both the time and the labour to be spent in assimilating the subject.

Considerable use has been made of photographic illustrations to exemplify the various components and installations. Through the willing co-operation on the part of the many firms, mentioned by name in the titles, whose products have been described, it has been possible to spread these examples over a wide range of manufacturing practice, representing a corresponding diversity of design and construction. Their kindness in furnishing these photographs, as well as much printed matter and information, is hereby acknowledged. Special reference may be made to the General Electric Co., Ltd., who have freely permitted the inclusion of engineering data from their records, notably in the Appendix.

The composition of some of the chapters has been much facilitated through the permission accorded by the editors of certain technical journals for the reproduction of articles originally appearing in their columns. Indebtedness on this account is gratefully expressed to

*World Power* (Chaps. X, XI, XII, and XIV), *Engineering* (Chap. XIII), the *Electrical Engineer of Australia and New Zealand* (Chaps. I, IX, XV, XVIII, XIX, XX, and XXI), and the *Australasian Electrical Times* (Chaps. VII, VIII and XVII).

In conclusion, the author wishes to thank those of his friends and associates who have helped him in various ways. Among these should be mentioned Messrs. T. W. Dann and F. R. Combes, whose excellent work in preparing the drawings for publication has been of special assistance.

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# NOTE

In accordance with modern practice and the decision of the British Engineering Standards Association, temperatures have been expressed in Centigrade units throughout. For those who require the corresponding particulars according to the Fahrenheit scale, a simple conversion table is included in the Appendix, viz. Table 12, p. 337.

# I

## INTRODUCTION

THE application of the electric drive to industry has formed one of the most remarkable features of engineering progress during the past three or four decades, and has brought about an almost revolutionary change in the methods, conditions, and results of industrial operations. At the beginning of this period mechanical power for practically every purpose was derived from prime movers, chiefly heat engines operated by steam, gas, or hot air. To-day these have been very largely supplanted by the electric motor, and the change is still actively proceeding.

In the exceptional cases when the heat engine is working at its greatest advantage the unit is of large size, is operated under constant load, and is directly coupled to the driven apparatus. Under such circumstances the efficiency is uniformly good, the space occupied relatively small, the regulation simple, the cost of attendance a minimum, and the transmission losses almost zero. It is evident that in these situations there is the least to be gained by the use of electricity ; yet it is significant that the electric motor has deposed the heat engine from very many of them to-day. There is no question, therefore, that electricity is possessed of vital advantages that are enabling the driving of mechanical loads to be carried out more perfectly than is otherwise possible, removing the prime mover to the bulk supply station, where it is able to work at its maximum efficiency.

In the great majority of cases, however, operating conditions are far less favourable to the old order of things than in those to which reference has just been made. Very often the power demand is small, involving in a heat engine a relatively low efficiency and a relatively high cost of housing and attendance. The demand is also frequently variable, causing a still greater lowering of efficiency due to the increased engine losses at partial loads, and possibly entailing increased cost on account of control requirements. In many cases the driven machines are numerous or scattered, necessitating severe losses in power transmission, either through condensation in steam-pipes or through friction in belts and shafting. None of the above conditions, however unfavourable to the engine, will give rise to any appreciable diminution in the efficiency, economy, or convenience of the electric motor, which, moreover, is able to bring with it important advantages not previously available. The improvements introduced by the electric drive will therefore be in general of a very definite and tangible description.

In common with important developments in other fields, the application of electric motive power was a gradual process and depended for its success upon more than one independent factor. At the beginning of the period under discussion the motor, at least in its D.C. form,

had just emerged from its experimental state and had begun to demonstrate its suitability for the majority of industrial tasks. Cautiously at first, but to a steadily increasing extent, it was installed for the provision of small and moderate amounts of mechanical power, until in a great many situations its use came to be regarded as almost a matter of course.

But although the motor continued to progress in design and construction, especially as regards its A.C. varieties, there were for a long time certain situations, largely among the heavy industries, where the conditions of work were so severe that its introduction appeared to be out of the question. The number of these cases was reduced somewhat through the continued development of the motor itself ; but even when it had almost reached its present state of perfection there still remained a residue of notable functions that demanded a higher degree of robustness and reliability than could be claimed by the electrical apparatus. This partial failure has been effectively converted into a complete success by the developments in heavy-duty and automatic control gear that were initiated about half-way through the period. Thus at a time when it might have been expected that the progress of the electric drive would slacken, the new factor took charge of the situation and development has proceeded more rapidly than ever before.

The importance of the improved control apparatus can hardly be exaggerated. It has formed with the motor a combination possessed of almost unlimited capabilities. Its functions have proved complementary to those of the machine ; for it has added strength where the latter was weak, and has effectively filled out the utility curve to a constant high level of excellence. Where protection was required by the windings or mechanical components, this has been afforded without risking any cessation of activity. When high rates of acceleration were essential, the maximum compatible with safety is assured at every start. Where the most capable or fatiguing attendance was needed, this has been provided to an exactly uniform degree, neither skill nor strength being demanded of the attendant. When the cost of an operator must be dispensed with altogether, the motor is put through its cycle of duties by the control gear entirely without human guidance. All these attributes, and more, have been added to the already great advantages of the electric motor, bringing about an enormous increase in its adaptability for any class of work that it may be called upon to do, for any position in which it may be located, and for any treatment it is likely to receive at the hands of human and other agencies. Thus it can be stated as a rule that there is no industrial purpose to which the steam, internal combustion, or other engine is at present applied that would not be better carried out electrically.

The present-day supremacy of the electric drive can be best illustrated by considering an extreme case, such as the operation of a colliery mine-hoist. In such a situation, where the cost of fuel is almost negligible, the steam-engine has an initial advantage that would put its rival completely out of the running unless the latter possessed a sufficient margin of superiority in its other attributes to counterbalance this

important factor. Now a study of the principal requirements of the situation is full of significance. In the first place, it is essentially a heavy-duty proposition, since great power must be developed at a high rate of acceleration. Secondly, extreme reliability of operation is demanded, as human life would be directly endangered by any irregularity. Since, therefore, a great and increasing number of mine hoists are being electrically operated, many taking their current from the ordinary supply authorities, it follows that to-day the electric motor has been endowed to an outstanding degree with just those qualities in which it was formerly found wanting. It is noteworthy that the result in this, as in most cases, has been achieved not by one, but by a number of widely different types of control gear, all having practically identical characteristics but each accomplishing its purpose in some special way that renders it more closely adapted for some kinds of pit than for others.

It is evident, therefore, that an extensive replacement of existing methods of drive must take place in the near future. This change is, as a matter of fact, already in progress, but is retarded by a number of quite usual causes, the chief of which are lack of knowledge, conservatism, and the high capital value of existing gear when in good condition. Of these, the two last will disappear as time goes on; it is the chief object of these pages to assist in dealing with the first factor, by supplying information as to the principles, nature, and design of modern electric control gear.

Such a subject depends closely upon the characteristics, first of the motors that are to be controlled, and secondly upon the loads that have to be driven. The author has therefore prefaced a consideration of the various types of control equipment with a short inquiry into the capabilities and peculiarities of the chief forms of motor employed in industry; and in order that the reasoning and design details that follow may be based upon the surest foundation, this preliminary theory has been deduced as far as possible from first principles. After the available pieces of control apparatus have been described, the remaining chapters will be concerned with their application to particular types of driven load, which have been so selected as to include those that are usually met with in industrial work to-day.

In these times of rapid engineering expansion it is inevitable that novel and unusual control requirements will be met with which are not completely represented in the examples quoted in the latter portion of the book. Care has been taken, however, to show how any set of characteristics can be combined into a control scheme; and by regarding the fully detailed equipments as instances of such constructive design, the reader should be able not only to understand but to produce a scheme suitable for any special conditions.

# II

# DIRECT CURRENT MOTORS

ONE of the great advantages possessed by motor drive over that employing steam or gas engines is derived from the varying characteristics with which an electric motor may be endowed by variations in the design of its windings, quite apart from further modifications which may be effected by means of appropriate control gear. It is obvious that the correct application of the motor is only possible when the characteristics of the various types are fully understood, and it is therefore proposed that this and the following chapter shall contain as complete an account as possible of the theory of the electric motor.

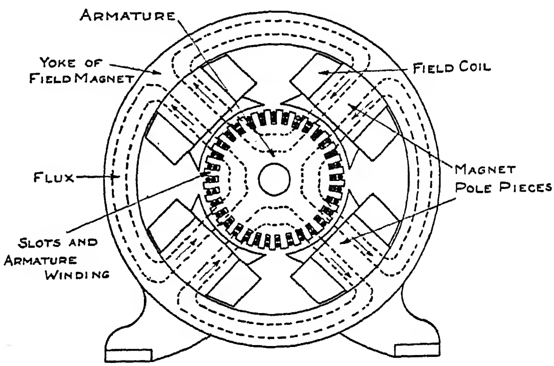



*Fig.* 1. Principal components of D.C. motor, showing flux paths.

To begin with, it should be understood that the motor is really included in the term ' dynamo ', the latter constituting a generator when it converts mechanical into electric power, and a motor when it carries out the reverse operation. The functions are literally interchangeable, in that any given machine may be employed (under proper conditions) in either capacity. It is important to realize this fact, since the principles of design and construction are the same for each of the two functions.

Now a D.C. dynamo consists essentially of two main parts, namely the field magnet and the armature, of which the first is practically always the outside stationary component in the cases now under consideration, while the armature is the rotating inner element. The purpose of the field magnet is to create the flow of magnetic lines of force, or ' flux ' to use its technical name, which passes in and out of the armature, very much as is shown in Fig. 1. It is therefore composed of iron or steel, and has ' poles ' projecting inwards upon which the

field coils are wound. When a current is passed through the latter the poles become magnetized, or in other words they give rise to a magnetic flux.

The armature is also an iron core wound with coils, which are disposed in slots evenly spaced round the periphery. As the armature rotates, therefore, these coils cut through the flux from the field. Now it is an established fact that when electrical conductors cut magnetic lines of force, an E.M.F. (electromotive force) is always developed, which, if the circuit is completed, will cause a current to flow. Connexion is made to the armature conductors for this purpose by means of sliding contacts formed by the commutator and brushes, the former being a ring of insulated copper bars joined to the armature winding at regular intervals, and the latter consisting of stationary carbon blocks pressed against the surface of the copper bars and connecting with the external circuit.

Except as far as size is concerned the first electric machines much resembled the small magneto generators that are employed in connexion with the ignition of internal combustion engines. The magnet was horseshoe-shaped and had two poles at its extremities ; and in the very earliest models it was permanently magnetized. Now, however, a much stronger and more symmetrical design of magnet is always employed, which is electrically excited, and is circular in shape, as shown in Fig. 1. The exact number of poles does not matter very much as far as the power of the machine is concerned, since the same amount of flux will come from one big pole as from three smaller ones each of one-third the sectional area. The example in the figure has four poles, but it is possible to design motors possessing the same capacity, speed, and voltage, having two poles in one case, four in another, and six in a third. The chief difference between the various models is in their proportions, the machine with relatively few poles being longer and smaller in diameter than that with many. This principle is of importance when it is desired to produce a motor for rapid reversing service, which shall possess as little inertia as possible, in which case the small-diameter armature secures a decided advantage. Motors of the latter type will be referred to later, when machine tool control is being discussed, in Chap. XXI.

The dynamo is then a machine in which magnetic lines of force are cut by conductors, producing an electromotive force capable of giving rise to an electric current. The exact voltage that is generated depends entirely on the rate of cutting lines, and is raised by any change that increases this rate, such as an increase in the speed, or the number of conductors, or the number of lines of force. If the armature is turned, for example by an engine, then a voltage is developed, and the machine functions as a generator. But if a voltage is already in existence, and is supplied to the stationary machine, then the armature is revolved, producing mechanical power, and the machine functions as a motor.

Now the theory of the motor is a little more complicated than that of the dynamo, since there are two voltages present, viz. that derived

from the line and applied to the armature, and that developed by the armature itself; for it must be remembered that the armature conductors cut the flux from the field as soon as rotation begins, and hence produce an E.M.F. on their own account, just as with a generator. These two voltages oppose each other (as demanded by the principle of the conservation of energy), and it is therefore the net voltage, or the difference between the two, that is available for passing current through the armature. This may be expressed in symbols thus:

$$I=\frac{E-e}{R}.$$

The two voltages are termed the applied voltage ($E$) and the back or counter E.M.F. ($e$) of the armature respectively. The symbol $R$ represents the resistance of the armature circuit, and $I$ is the current.

This relationship will explain many of the characteristics of the motor. For example, if the line voltage be applied when the armature is at rest there is no back E.M.F., and a very large current will pass through the armature, as indicated by the ordinary Ohm's Law formula. Again, if it be supposed that the motor is running light and has attained full speed, the back E.M.F. very nearly equals the applied voltage, and the current given by the equation is that just sufficient to overcome the no-load losses of the machine. It will be seen that if the efficiency of the machine were 100 per cent. then the two voltages would be equal, making the current zero.

The turning effect of a motor, or the *torque* as it is technically named, is the force between the armature and the field, tending to rotate the former. Since this force is an interaction between two magnetic members, its strength is proportionately affected by a variation in the strength of either. Thus the torque is proportional to the product of the field strength and the armature strength; or what comes to the same thing, to the field strength multiplied by the armature current.

It is necessary to consider here the effect of varying the field strength upon the speed of the motor. Suppose the field were weakened to some extent by inserting resistance in its circuit. The immediate effect would be to lower the back E.M.F. generated by the machine, and this would cause a corresponding increase in the current that was able to pass through the armature. Then assuming the connected load to be of constant torque, the speed would be able to rise until the consequent increase of the back E.M.F. had restored the balance by reducing the current to just that amount required to rotate the load at that speed. This raising of the speed by the weakening of the field is the opposite of what might have been expected at first sight, and its cause should be clearly understood. The converse action is naturally true also, in that strengthening the field reduces the speed of the motor.

With the above facts in mind the behaviour of various types of D.C. motor may be understood by considering the effect of the various methods of exciting the field. These are shown diagrammatically in Fig. 2, which although containing three main components only, viz. the

armature, shunt field, and series field, is sufficient to represent all the various types of windings.

First, the field may be wholly excited by means of a winding connected in parallel with the armature, in which case the machine is known as a 'shunt' motor. This is the simplest type to understand, since the field is connected directly across the mains. Hence the exciting current is independent of the load and, except for a minor effect which will be discussed shortly, the field strength is dependent solely upon the supply voltage. Since the speed of a D.C. motor under constant voltage varies only when the field changes, this winding gives a constant speed characteristic. When the load mechanically connected to its shaft is zero, the motor takes just sufficient current from the line to overcome the no-load losses; but as the load is increased the armature current automatically increases in proportion. This action continues up to values of the current very much in excess of that which can safely be passed through the armature for any length of time. In fact the characteristic of the shunt motor is that it endeavours to rotate any load at a constant speed even if it suffers destruction while so doing. As will be shown later, however, exactly constant speed is practically unattainable, partly owing to the minor field variation to which reference has just been made, and partly because of a loss in the armature that increases with the load.

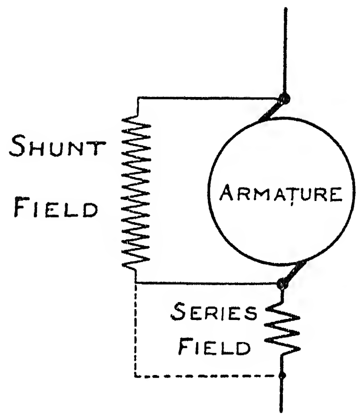



*Fig.* 2. Field connexions for D.C. motors.

Secondly, the field may be entirely excited by means of a winding connected in series with the armature, producing what is called a 'series' machine. In this case the same current flows through both armature and field, and therefore the field strength, instead of being constant as with the shunt motor, fluctuates with the armature current. For example, when the circuit is first closed the current is heavy and the field strength is high, producing a high starting torque. If the motor is heavily loaded, its speed remains low and its torque is relatively great. Should the load, however, become light, the current is reduced and the field is weakened. The speed therefore increases considerably and the torque is correspondingly reduced. If the load is reduced to nothing, as might occur through the breaking of a belt, the field strength almost vanishes, and the speed is increased, usually until the motor bursts. In this connexion the very appropriate replies of a student to his professor may help the memory. He was asked what would happen if the shaft-coupling of a series motor broke, and answered, 'It would

run away '. 'What would you do ?' was the next query, to which he replied, 'The same as the motor'; and it must be confessed that under some circumstances his action would be fully justified.

The purposes for which the above two simple types of motor are adapted can now be generally stated. The shunt machine tends to operate every load, however big, at constant speed. Since the torque is the product of the unvarying field and the armature current, it varies directly with the latter. This motor is therefore suitable for constant speed work in general, such as the operation of line shafting. The series machine, on the contrary, varies its speed, and varies it widely, with every change of load. Since both the factors which produce the torque, viz. the armature and the field, increase and decrease together, the torque varies to a much greater extent with changes of speed and load than in the case of the shunt motor. The series type is therefore especially adapted for purposes which require a strong starting torque, such as electric traction, haulage, and crane work. It cannot safely be employed, however, with any load which may decrease to a very low value, since that would entail the generation of a dangerously high speed; and in this classification should be included those that may reach zero value as the result of an accident such as the breaking of a belt.

The compound motor is one possessing both types of field excitation, which may be arranged in two ways, as indicated by Fig. 2. The connexion of the shunt field shown by the lower full line is known as the 'short shunt' connexion, and that indicated by the dotted line is known as the 'long shunt'. As far as motors are concerned there is very little difference between the effects produced by the two, and in practice the shunt field is always connected right across the mains at starting, giving the long shunt arrangement.

In order to understand a compound motor it should be treated as a cross-breed both in construction and in qualities, as the characteristics occupy an intermediate position between those of the shunt and series machines. The proportion of the excitation which is normally derived from the series coils may be varied according to the characteristics desired, but it is usually well under half the total, the major portion of the field strength thus coming from the shunt windings. The effect of adding the series field is to make the speed vary, though not to a dangerous extent, and to give the motor a stronger torque at low speed than at high. For example, motors are designed in which the series field is about 20 per cent. of the full excitation, enabling the motor to start a heavy load more readily than the plain shunt motor; and the series turns may be automatically cut out when full speed is reached. On the other hand, machines are sometimes specified in which the field is almost entirely supplied by the series windings, there being just sufficient shunt field added to obviate the possibility of the motor bursting itself when the load is entirely thrown off.

One of the principal uses to which the compound motor is put is the operation of machinery that makes a sudden demand at one or more

points in the revolution of its spindle, and travels idly during the remaining portion. In such a case it is of advantage to store energy during the idle part of the travel which can be given out when the actual work is being done. A number of instances of this type of load will readily occur to the reader, the simplest examples probably being punching and shearing machines. Such apparatus are generally equipped with a fly-wheel, in which the energy is stored ; but it should be realized that storage is impossible unless the motor has variable speed characteristics. If, for example, a shunt motor were used to do this work, it would endeavour to drive the spindle at a constant speed whatever the opposition, running light when no energy was absorbed, suffering a heavy momentary overload during the heavily loaded periods and probably sparking and overstressing itself in the process. Since a fly-wheel can only store energy by increasing its speed, and give back this energy by slowing down again, it does not assist matters at all with a shunt machine. The correct practice is, therefore, to employ a compound motor with a fly-wheel for such heavily fluctuating work.

There is a further function of the compound winding which is responsible for its wide use with large motors required for ordinary constant-speed service, and its former considerable use with small motors as a counter-compound winding. In these cases it is employed to correct the variations of speed of the shunt motor, arising from the two effects that have been previously mentioned. These are voltage drop in the armature winding and armature reaction, respectively. The former consists of the usual fall of potential that occurs when current is traversing a resistance, and it is proportional to the current flowing. Its effect is to reduce the active E.M.F., and thus it causes the speed of a shunt motor to fall off as the load rises. The second effect consists of an interaction between the magnetism of the field and that of the armature, the result of which is to distort the flux and therefore to weaken it to a certain extent. Since the field strength is thus affected more or less in proportion to the load current, the effect tends to produce an increase in the speed of the shunt motor as the load rises, and is hence the opposite of the previous one.

These two effects occur in different proportions in large and small motors. In most large high-speed machines the armature reaction effect preponderates over the other, and hence the speed of a large shunt motor may increase to some extent with the load. In order to overcome this a weak compound winding is added to motors that are large enough to justify the addition. But with small models the armature drop is the larger of the two, and produces a small falling off in the speed as the load increases. With the brushes maintained in the central position the variation of speed is not a large one, and for almost all purposes the motors can still be regarded as virtually constant-speed machines. If, however, it is essential that the speed should be exactly uniform, the falling-off tendency can be corrected by the addition of a reverse-connected compound winding, which weakens the field as the load grows larger. This produces the so-called counter-compound motor.

At one time counter-compound machines attained quite a vogue, as the need for exactly constant speed was much exaggerated ; and, in addition, the motors of that date possessed a more fluctuating speed characteristic than present-day models, largely owing to the general practice of displacing the brushes to diminish sparking. The counter-compound type is now recognized to be much inferior as regards reliability to all the others, and its use is confined to cases where constant-speed requirements are especially exacting. Its defect can be understood when it is realized that the shunt and series field are opposing each other, and hence the electrical equilibrium is becoming

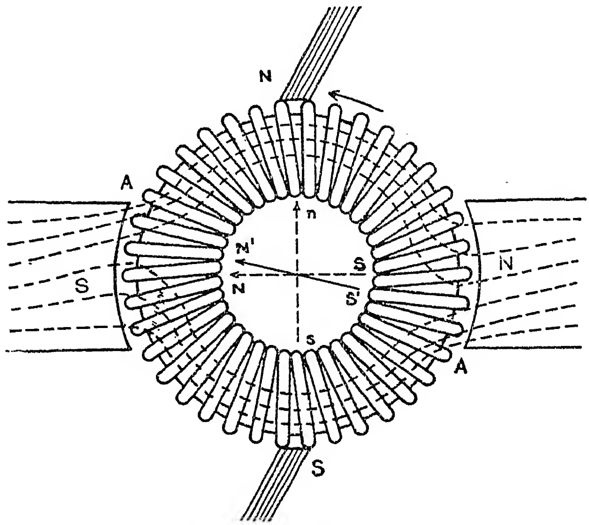



*Fig.* 3. Magnetic circuit of a D.C. motor, showing distortion of flux through armature reaction.

more unstable as the load increases. Satisfactory operation can only be relied upon as long as the load is kept within the normal limits, the effect of an overload, or even over-rapid starting, being to weaken the field very considerably. Upon the occurrence of unusual loads machines of this kind are actually known to develop enormous speeds, which may be followed by a dead stop under load and an equally violent acceleration in the opposite direction, due to the field first weakening to zero and then reversing.

It will be of advantage to discuss somewhat more fully the nature and causes of armature reaction, and in this connexion the diagram in Fig. 3 will be of considerable assistance. In this the windings on the armature are disentangled for the sake of simplicity and shown as though they were wound round a ring, instead of the drum pattern of core which is the standard to-day. The brushes are also shown as

though they were resting upon the actual conductors, instead of upon commutator bars leading to these. The windings will then be seen to be connected by the brushes in the form of two parallel portions (for the two-pole machine shown), and the result of the passage of the current from brush to brush will be to magnetize each half in the same direction. Thus the net result is to produce a magnetic pole under each brush. In the case of a motor rotating in the direction shown by the arrow, between field magnets having the polarity indicated, the effect will be to produce a north pole at the upper brush and a south pole at the lower one. This polarity interacts with the field flux, distorting it

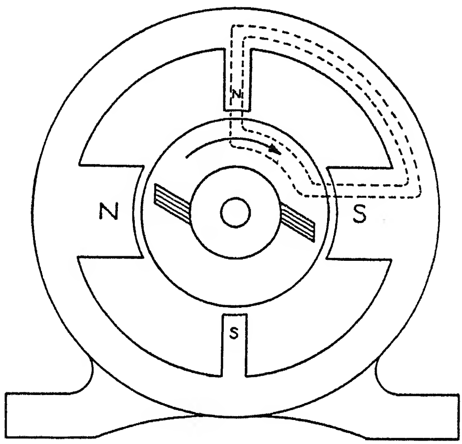



*Fig.* 4. Two-pole D.C. motor, showing location and polarity of auxiliary 'commutating' poles and their effect upon the flux through the midway conductors.

as shown in the figure, so that an undue flux density is developed at the upper horn of the south pole and the lower one of the north pole.

The effect of this distortion is twofold. First, the field is weakened to a slight extent through the overcrowding of portions of its path; secondly, the conductors under the brushes, instead of sliding through the lines of force, actually cut a certain amount of flux, producing an E.M.F. in the windings that are short-circuited by the brush itself. This may give rise to heavy momentary currents in these windings, and destructive sparking if the effect be sufficiently pronounced. In point of fact, a weak voltage in the opposite direction is beneficial and in many cases even essential, as it assists the current in these windings to reverse exactly while they are short-circuited, so that they may take their place in the circuit on the other side of the brush without disturbance.

Until recently it used to be the custom to obviate this sparking by moving the brushes themselves until a sparkless position was reached. In the case shown in Fig. 3 they would have been turned in a clockwise

direction, and eventually would have reached such a position that the conductors under them did not generate a harmful E.M.F.; but by rotating the brushes the polarity of the armature itself is now rotated also, and this increases the actual distortion of the flux, rendering it necessary for them to be shifted still farther. Not only would a considerable displacement of the brush-rocker thus be needed, but the correct amount would vary with the load on the machine and the setting of the field rheostat, and it would actually be in the wrong direction if the rotation were reversed.

Nowadays it is customary for all but the very smallest machines to be provided with what are called commutating poles for overcoming this effect. These consist of small auxiliary pole-pieces round which the armature current is passed by means of a weak series winding. Their position and effect are indicated in Fig. 4, which shows that the polarity is the same as that of the main pole that the armature has just left. It must not be supposed that armature reaction can be cancelled by this device; it is in fact frequently enhanced thereby. Sparkless commutation is, however, brought about by the correction of the flux in the 'commutating zone'.

¶ Speed Adjustment.—The effect of field variation in altering the speed of a motor is utilized for speed adjustment purposes by employing a rheostat to modify the excitation. By this means it is easy to design machines having running speeds extending over a range of 3 : 1; while a range of 5 : 1 can be obtained when necessary.

Two points, however, must be borne in mind when motors are to be speeded up in this way. First, if a given motor is to be capable of running at a speed of, say, three times the normal value, it must be made mechanically strong enough to withstand the disrupting forces at that speed. Since the peripheral velocity of the armature is limited to a given maximum figure, actually from 3,000 to 4,000 ft. per min., the motor must be designed to give full load at the minimum speed, which in this particular case will be at most one-third of the permissible value. The armature conductors must also be made of sufficient sectional area to carry the increased current necessary to overcome the torque when the field is weakened. Thus the motor will require to be much larger and therefore more costly than when designed for ordinary constant-speed service.

Secondly, the weakening of the field has a disturbing influence on the running of the machine, owing to the enhanced effect of the armature magnetism on the flux. If there are no commutating poles an increase in speed exceeding about 70 per cent. renders sparkless running impossible. This defect is corrected by the interpoles, but even then a motor with a bigger range than 2 : 1 is subject to a rhythmical weakening and recovery of the field strength that causes 'hunting' of the speed. A series 'stabilizing' field winding, however, will counteract the effect and is always used on such motors.

¶ Load Currents.—The chief numerical data required in the design of

control gear for D.C. motors are the load currents for the various sizes and voltages. These can be calculated from the formula :

$$I = \frac{H.P. \times 746}{V \times \eta},$$

where $V$ = rated voltage
and $\eta$ = efficiency.

The latter quantity varies from about 75 per cent. for 1 H.P. motors to 90 per cent. for 50 H.P. In the great majority of cases met with in industrial work the values can be obtained from the following list :

TABLE 1. NORMAL FULL-LOAD CURRENTS OF D.C. MOTORS

| *Size of Motor B.H.P.* | *Voltage.* 110. | 220. | 440. | 500. | 600. |
|---|---|---|---|---|---|
| ¼ | 3·1 | 1·6 | 0·8 | 0·7 | 0·6 |
| ½ | 5·6 | 2·8 | 1·4 | 1·2 | 1·0 |
| 1 | 10 | 5 | 2·5 | 2·2 | 1·8 |
| 2 | 18 | 9 | 4·5 | 4·0 | 3·3 |
| 3 | 26 | 13 | 6·5 | 5·7 | 4·8 |
| 4 | 34 | 17 | 8·5 | 7·5 | 6·2 |
| 5 | 42 | 21 | 10 | 9·2 | 7·7 |
| 7·5 | 61 | 30 | 15 | 13 | 11 |
| 10 | 80 | 40 | 20 | 18 | 15 |
| 12·5 | 99 | 49 | 25 | 22 | 18 |
| 15 | 117 | 59 | 29 | 26 | 21 |
| 20 | 154 | 77 | 38 | 34 | 28 |
| 25 | 191 | 95 | 48 | 42 | 35 |
| 30 | 227 | 114 | 57 | 50 | 42 |
| 35 | 265 | 132 | 66 | 58 | 48 |
| 40 | 300 | 150 | 75 | 66 | 55 |
| 45 | 340 | 170 | 85 | 75 | 62 |
| 50 | 375 | 187 | 93 | 82 | 68 |
| 60 | 450 | 225 | 112 | 99 | 82 |
| 70 | 520 | 260 | 130 | 115 | 96 |
| 80 | 595 | 298 | 149 | 131 | 109 |
| 90 | 665 | 333 | 166 | 146 | 122 |
| 100 | 740 | 370 | 185 | 163 | 136 |
| 125 | — | 460 | 230 | 202 | 168 |
| 150 | — | 550 | 275 | 242 | 202 |
| 175 | — | — | 320 | 282 | 235 |
| 200 | — | — | 365 | 322 | 268 |
| 225 | — | — | 410 | 360 | 300 |
| 250 | — | — | 456 | 402 | 335 |
| 300 | — | — | 545 | 480 | 400 |
| 350 | — | — | 637 | 561 | 467 |
| 400 | — | — | 728 | 640 | 533 |
| 500 | — | — | 908 | 799 | 665 |
| 600 | — | — | 1,110 | 977 | 814 |
| 800 | — | — | 1,445 | 1,272 | 1,060 |
| 1,000 | — | — | 1,803 | 1,586 | 1,322 |

It should be understood, when using such a table as this, that the efficiency of a motor possessing a given horse-power is by no means a definite quantity, and only average results can be tabulated ; for the slower the speed at which a machine is designed to run the greater is

the proportionate loss in the field and the iron, and therefore the lower the efficiency. Three models at least are usually listed by manufacturers for each horse-power rating, and the value given above will therefore be appropriate for that running at the mean speed.

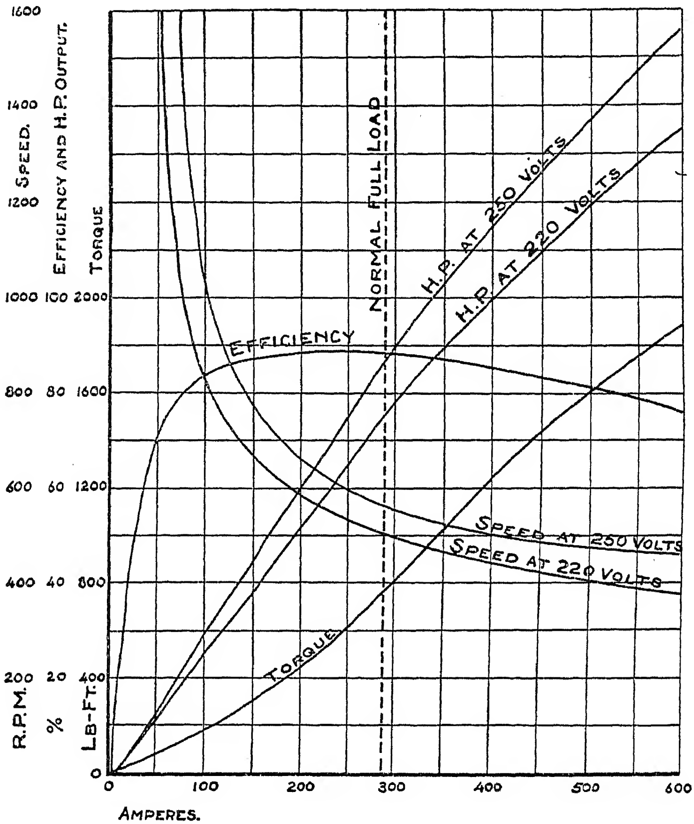



*Fig.* 5. Characteristic curves of 220-volt 75 H.P. series motor.

¶ CHARACTERISTICS.—By way of exemplifying the characteristics of a D.C. motor; curves are given in Fig. 5 for the variation with armature current of the horse-power, torque, speed, and efficiency of a particular model, in this case constituting a series machine of the mill type designed for a normal output of 75 H.P. at 220 volts. In order to show the effect of change of voltage, separate curves are given for the speed and horse-power for an increase of 30 volts, or about 14 per cent.

The typical falling speed characteristics of the series motor, and the concave torque line, are to be observed. For a shunt motor the former would be an almost horizontal straight line, and the latter an almost

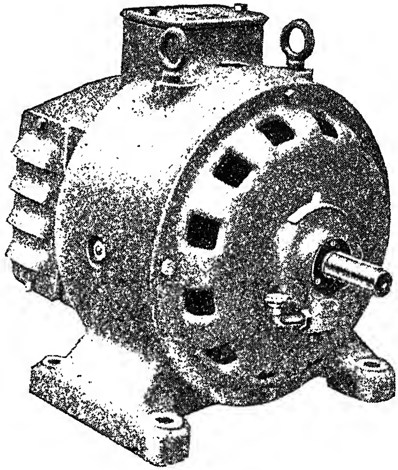
straight line through the origin, each intersecting the respective series curve where it crosses the vertical normal full-load line, shown dotted. For a compound motor the curves would be intermediate in position and shape between those for the series and shunt, their exact configuration depending upon the amount of compounding.

¶ Mechanical Features of the Electric Motor.—Motors having approximately the same electrical design may be modified mechanically in a number of important respects that merit a brief notice. To begin with there are three distinct types of frame, differing in robustness and mode of assembly in accordance with the requirements of certain important situations. These are the ordinary industrial, the traction, and the mill types respectively.

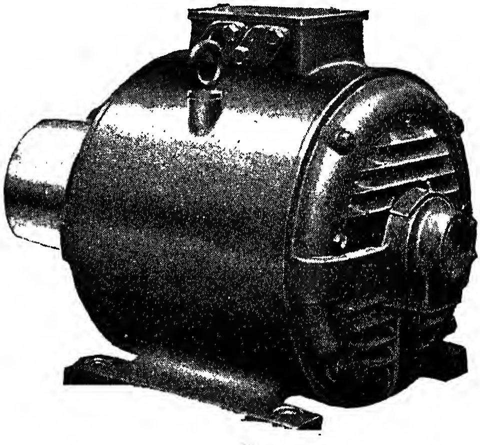
The first of these needs little explanation. It is suitable for the great majority of industrial functions and may be especially adapted for various locations by minor modifications of the frame, as shown in Fig. 6, chiefly to afford a required degree of mechanical protection against unfavourable housing conditions. For dry interior situations, where foreign matter is not likely to get in among the windings, the ordinary open pattern may be employed. The motor, however, may be totally enclosed by the use of solid end-shields, preventing the ingress of moist air or spray, as well as of less permeable objects. Since the output of nearly every electrical apparatus is directly proportional to the dissipation of heat from its surface by air circulation, total enclosure considerably reduces the horse-power capacity, usually by something over 30 per cent., and it is therefore avoided as far as possible.

There are intermediate degrees of enclosure that produce a much smaller effect on the output and are effective against less troublesome conditions. A 'protected' or 'enclosed ventilated' frame serves to prevent accidental contact on the part of a workman, and excludes tools and other objects that might be dropped upon it. The ventilation is scarcely interfered with, especially as motors are now almost always fitted with a fan at one end of the armature. A 'drip-proof' frame has openings of the louvre description; while a 'pipe-ventilated' machine is virtually a totally enclosed pattern, there being provision for an inlet and exhaust pipe, or inlet pipe only. In the latter form the air emerges through a port opening downwards into the room. Pipe-ventilation is naturally expensive and is only used when effective cooling is demanded in the most difficult surroundings.

The traction motor was designed to resist the electrical and mechanical shocks and the unfavourable location attending tramway or railway working, and is also adopted for some purposes in stationary practice. At one time it was tried for the operation of rolling-mill auxiliaries, but was discarded in favour of the special mill motor, which is a further development in the direction of robustness and of quick assembly. More will be said regarding this type in Chap. XVIII.



A. Protected or enclosed ventilated D.C. motor.



B. Protected squirrel-cage motor.

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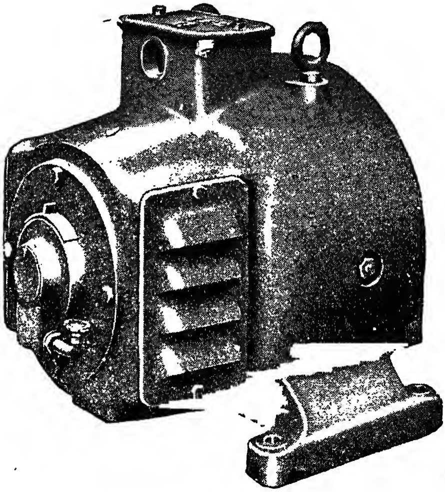
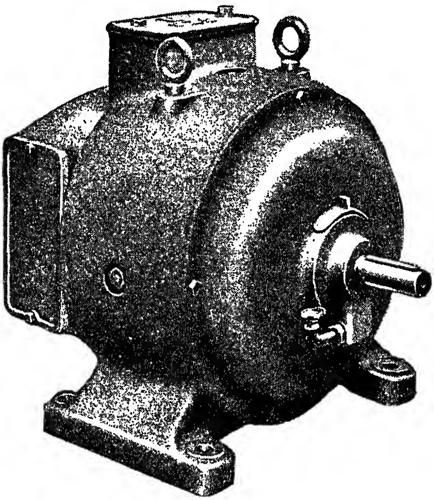
*Fig.* 6. Types of frame for D.C. and A.C. motors.



C. Drip-proof motor.



D. Totally enclosed D.C. motor.

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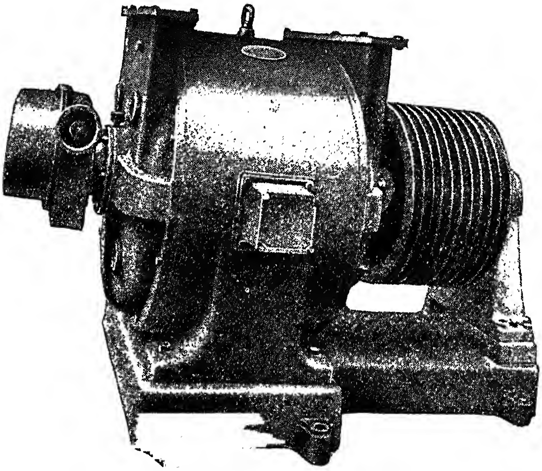
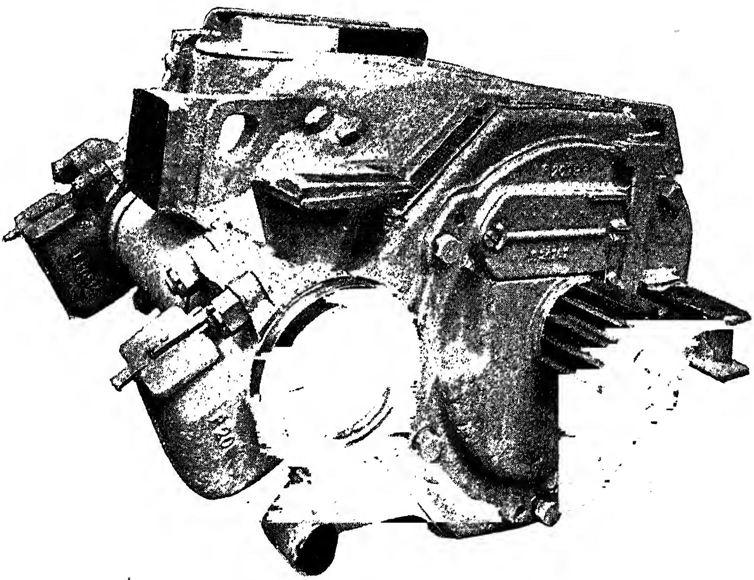
*Fig.* 6. Types of frame for D.C. and A.C. motors.



E. Pipe-ventilated slip-ring A.C. motor, with rope pulley.



F. Traction motor (D.C.).

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*Fig.* 6. Types of frame for D.C. and A.C. motors.

## III

## ALTERNATING CURRENT MOTORS

THE principles discussed in the previous chapter relating to the theory and design of the D.C. motor hold good with but few reservations in the A.C. case also. All motor action, in short, is based upon the production of an E.M.F. when a flux is cut by a conductor, and conversely upon the development of mechanical force when a conductor carrying a current is in a position to cut lines of force. The modifications in the design of the motors when they are to be energized by an alternating current are due partly to special difficulties and partly to additional facilities introduced by this form of electricity.

It is well known that when the voltage applied to a D.C. motor is reversed, the armature continues to rotate in the same direction, since the polarity of both field and armature are changed simultaneously. There is thus no inherent barrier to the operation of the motors that were described in the last chapter by an A.C. supply. Two peculiarities of a non-continuous current are responsible, however, for a marked alteration in the conditions ; and unless full consideration be accorded to these, unsatisfactory results, to say the least, will be given. The phenomena in question are transformer action and reactance.

The effect of the former is that any two circuits upon the same iron core are able to influence each other in such a way that a change in the current flowing in the one causes an E.M.F. to appear in the other, due to the production of a change of flux in the iron. An alternating current in the one will thus induce an alternating E.M.F. in the other, and the action of all transformers is based upon this principle. Every conducting ring or sheet that in any way constitutes a circuit upon the core of an electrical machine or apparatus, or through which the flux in the core passes, will function as a short-circuited ' secondary winding ', and will be traversed by a heavy ' eddy ' current when the main winding is energized. Even the iron or steel of the core itself comes within this category, and will generate heavy circulating currents if steps be not taken to prevent them. Since loss of power and serious heating would be caused thereby, the cores and all other parts of the magnetic circuit are laminated by being built up of sheets not thicker than about 0·015 in., which are usually coated on one side with insulation.

The current in a D.C. winding flows in accordance with Ohm's law, being inversely proportional to the resistance only. With alternating currents the inductance of the winding also checks the flow of current, and is the more effective the higher the frequency. The current is thus also inversely proportional to a factor called the reactance, and represented by the symbol $X$. Then if $L$ is the inductance of a circuit and $f$ the frequency, $X = 2\pi fL$. The inductance being pro-

portional to the square of the number of turns, it will be seen that the opposition to the passage of the current is very great for shunt as compared with series windings, and the design of the former is attended with no little difficulty. In addition to the reduction in the magnitude of the current, its growth and decay are delayed; or, in other words, its phase-angle is retarded or its power factor reduced. Since in a shunt coil the reactance is so great as to render the resistance almost negligible, the angle of lag approaches the maximum of 90 degrees; and the power factor, which is the cosine of the angle of lag, is thus very low.

¶ Shunt and Series Motors.—It will now be understood why the shunt motor, as described in the last chapter, is very difficult to design for A.C. working on account of the high reactance of the field winding. The series machine, however, does not possess the same drawback, and it is in extensive use, in a suitably modified form, for A.C. railway traction. It would be available also for stationary work of the type served by the D.C. series motor, but there are two considerations that prevent its use from becoming common. These are the preponderance of polyphase distribution, whereas in its usual form it requires a single-phase supply; and the existence of the induction motor, which fulfils almost the same purposes in a more satisfactory manner. With regard to the former objection, it is possible to design the series motor as a three-phase machine, but it is relatively complicated and is little used.

¶ The Repulsion Motor.—A variant of the series type known as the repulsion motor is of somewhat more interest to industrial engineers than the original form. If the armature connexions are removed from the main leads and the brushes short-circuited instead, a current will be induced in the armature conductors which will produce rotation very much as before. This principle is sometimes employed in connexion with the starting of single-phase induction motors, to be dealt with below; while the wide adjustment of the speed that can be effected by merely moving the brush rocker has caused the repulsion motor to be applied to the driving of spinning-mules, and some other machinery where this feature is of special importance in connexion with an A.C. supply.

¶ The Synchronous Motor.—Alternating current is generated by means of a dynamo resembling the D.C. machine, with its field excited by direct current. But instead of the armature current being commutated, the ends of the winding are brought out and deliver it in an unrectified form. Such a machine acts as a motor when the armature is supplied with A.C., and is the most efficient A.C. type; but it suffers from two serious disadvantages that have until recently rendered it unsuitable for wide industrial use. The first of these is that a D.C. supply is required for the field as well as an A.C. for the armature, and usually has to be provided by a small 'exciter' dynamo mounted at the end of the main shaft. The second is that the 'rotor' or rotating element (for the field magnet is more frequently revolved than the armature) must be running at full speed and the armature must be

generating an E.M.F. exactly in phase with that of the supply before it can be switched in. The pure synchronous motor, therefore, so far from being able to start under load, requires special motive power to bring it to full speed and may demand considerable skill in synchronizing it with the supply before it can be connected at all. In the combined synchronous-induction form, described later in the chapter, the latter difficulty is largely overcome.

In spite of these drawbacks the type is occasionally employed for comparatively large units that do not require frequent starting, on account of an important advantage it possesses over non-synchronous A.C. types. This is its capability of giving unity power factor with its field at normal strength, and actually developing a leading factor when over-excited. The synchronous machine can thus be made to compensate for a lagging phase-angle in other parts of the system. Since it is a usual custom for power companies to penalize consumers according as their power factor falls below unity, such a property is a very useful one.

A further valuable characteristic of the synchronous (including the synchronous-induction) motor is its absolutely constant speed, since it is compelled to rotate in exact synchronism with the supply current; and this property secures it further employment. Where a group of machines are required to run with a constancy of the order of 0·1 per cent., and more especially to maintain their speeds relatively to one another in exactly constant proportion, as in paper-making, this type of motor is sometimes used as an auxiliary to the main driving motor to equalize the speed by transferring differences in the loading conditions from one unit to the other. The armatures are then joined together in parallel, but are not fed from any supply.

¶ THE INDUCTION MOTOR.—By far the most useful A.C. machine for industrial drive, however, is one which has no counterpart in D.C. practice, and is known as the induction motor. This consists of, first, a polyphase stationary element or ‘ stator ’ resembling a field-magnet system in which the poles belonging to the respective phases follow one another in order, so that a rotating field is produced by the current; and secondly, a ‘ rotor ’ composed of conductors that are not connected to the line, but are short-circuited on themselves, except that provision may be made for the inclusion of resistance for starting, or less frequently for speed control. When the rotor is stationary it is being cut by the rotating field at its maximum rate, and a heavy current is generated in its winding. This develops a magnetism in the core, which produces a torque and causes the rotor to revolve in the same direction as the flux. As it accelerates, the difference in speed between the rotor and the rotating field, known as the ‘ slip ’, becomes less, and the E.M.F. produced in the rotor windings naturally decreases in proportion. If the motor is unloaded its speed almost reaches that of the rotating field, the slip being just sufficient to generate the small current needed to overcome the no-load losses of the machine. The

result of applying normal full load is to produce a slip of about 2 or 3 per cent.

The stator windings for a two-phase motor, with one pair of poles per phase, are shown diagrammatically in Fig. 7. If the rise and fall of such a current be studied, it will not be difficult to understand how the rotating field is produced. Suppose first that the current in phase *A* is a maximum. Then, as shown in the wave diagram on the right, that in phase *B* is momentarily zero, and the direction of the resultant magnetism is as represented by the arrow marked 1. A quarter of a cycle later phase *A* is zero, while *B* is now a maximum, and the direction of the flux is indicated by 3, having turned through 90 degrees. Half-way between the two positions the two currents are equal, each being cos 45 degrees times the maximum, or $I_{max.} \times 0{\cdot}707$. The resultant of the two magnetizing forces at 90 degrees to each other and

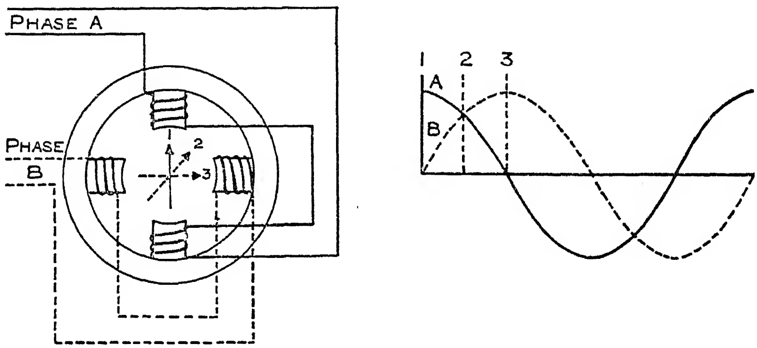



*Fig.* 7. Production of rotating field, illustrated by means of a two-phase stator.

of this magnitude is a force midway between the two and equal to $I_{max.}$, i. e. the previously found value. If this calculation were repeated at every point of the cycle a similar result would be given, and it would be established that a field of constant strength is produced, rotating at a uniform speed of one revolution per cycle. The same may be shown to occur with a three-phase current and winding.

Actually the coils are not wound on projecting or 'salient' poles as in the diagram, but are distributed in slots formed in a hollow cylindrical core. The use of a small air-gap is advantageous in that the power factor is directly increased thereby; and this distance is therefore made much less than with D.C. machinery.

With a two-pole stator winding such as that indicated, the maximum speed at 50 cycles per second would be slightly less than 50 revolutions per second, or 3,000 per minute. The full value quoted is called the synchronous speed, and is that at which the motor is usually rated to run; since even at full load the actual speed is only about 2 or 3 per cent. (the full-load slip) less than this. If the motor is rotated by external means at exactly synchronous speed, the power consumed

falls to zero ; while if it is revolved at slightly above this rate it functions as a generator, returning power to the line. This faculty is of great use for braking purposes, for example, when lowering a load on an electric crane.

Lower speeds are obtained by designing the stator and rotor with more than one pair of poles per phase. Thus a four-pole 50-cycle machine has a synchronous speed of 1,500 r.p.m., a six-pole 1,000 r.p.m., an eight-pole 750 r.p.m., and so on, the general formula being $3{,}000 \times \frac{2}{p}$, where $p$ is the number of poles. For any frequency, $f$, the speed is $60f \times \frac{2}{p}$, or $\frac{120f}{p}$, in revolutions per minute.

Two forms of rotor are employed in practice. That known as the 'wound' type possesses a three-phase winding, however many phases the stator may have. The ends are brought out to slip-rings and brushes, between which resistances are connected for starting. Many models incorporate a short-circuiting device whereby the rings are solidly joined together, and the brushes raised, by the forcing in of a push-rod or lever.

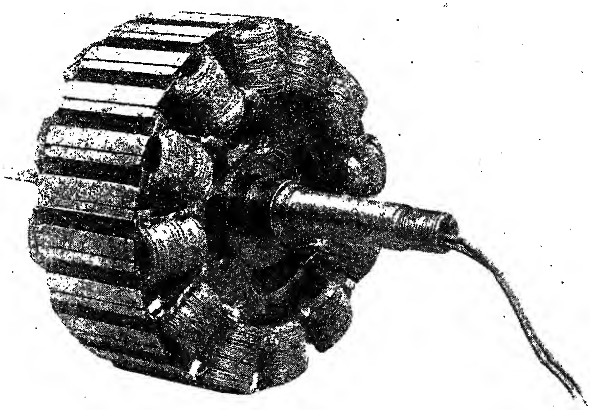
Since the scheme of any particular winding is obliterated when it is short-circuited, and since resistance is added only for starting, a simplified rotor is much used in which the conductors are merely brazed or soldered into a single ring at each end of the core, even the slot insulation being omitted. This is known as the 'squirrel-cage' type, and is mostly employed for purposes that do not demand a very high starting torque. An even simpler arrangement is adopted for 'pony' motors, used for starting synchronous motors and converters. In this case the rotor consists merely of an unlaminated iron core without windings, the rotor currents circulating in the core itself.

The single-phase induction motor is not so satisfactory a model as the polyphase. Since a rotating field cannot be produced by an unassisted single-phase current, special devices are required for starting. When the machine is running, however, interaction between the stator and the revolving rotor converts the pulsating field into a rotating one. If, therefore, a single-phase motor be run up by hand or other external means to say one-fifth of its rated speed, it will accelerate itself to full speed and be then capable of exerting full-load torque.

The provision of mechanical starting would be most inconvenient in the majority of cases and an electrical method is therefore necessary. The simplest expedient is to produce an auxiliary second phase for starting only, by inserting a considerable amount of reactance in a branch circuit fed from the common supply. There are two schemes for effecting this, namely, phase-splitting and pole-shading. With the former the stator has a complete two-phase winding, one phase of which need only be designed for temporary use. For starting the phase-angle of the main winding is advanced by the insertion of a resistance, or less frequently a capacity, and that of the auxiliary winding is retarded by an inductance included in its circuit. An approximate two-phase

current is thus developed that is able to produce a weak starting torque sufficient to run up an unloaded rotor.

Pole-shading is chiefly employed for small motors, such as those operating fans, where a very small starting torque is required. It is carried out by encircling a portion only of each pole on the stator with a short-circuited winding, usually consisting of a single copper ring. Heavy secondary currents are induced in these, which retard the phase-angle of the flux in the portions of the poles in question and form a pseudo two-phase arrangement producing a rotating field. The illustration in Fig. 8 shows the *internal* stator of a vertical slow-speed single-



*General Electric Co., Ltd.*

*Fig.* 8. Pole-shading of single-phase 'Freezor' fan motor.

phase fan, in which the shading-rings are clearly seen. The rotor is in this case in the form of an external collar.

A different solution of the problem is to convert the rotor into a repulsion motor armature for starting. To do this a small commutator is fitted, to which the windings are connected as with a D.C. machine. This and the brushes are in action when starting and a fair torque is developed, but a centrifugal device mounted inside the rotor comes into operation at about half speed, short-circuiting the commutator and lifting the brushes. It then becomes the equivalent of a squirrel-cage model.

The drawbacks of this device are the natural results of its elaboration. A motor so equipped is far more expensive than the ordinary pattern and is less reliable. The result of a sufficiently heavy overload would be to prevent the commutator from being put out of action, and since this gear is designed for 15 or 20 minutes' duty at most, damage through over-heating would be the result.

In addition to increased starting difficulties, single-phase induction motors possess somewhat inferior electrical characteristics as compared with the three-phase varieties. Their output is reduced to from 65 to 75 per cent. of that derived from three-phase models of the same size. Their overload capacity, power factor, and efficiency are less, while the no-load current is higher.

The effect of resistance in the rotor circuit of an induction motor is especially important as regards starting and control problems. Now the torque of a given unit is improved by any means that increases its power factor. When the rotor is stationary, and there is thus no back E.M.F., a heavy current flows if the motor is switched on with the rotor resistance at its normal low value. The power factor, however, is low, being of the order of 45 per cent., and the available starting torque is reduced thereby. Thus although the starting current might rise to as much as six times normal full-load value, a torque of 1·25 times normal is seldom exceeded. But by adding resistance to the rotor circuit the power factor is increased and with it the torque, while the starting current is reduced.

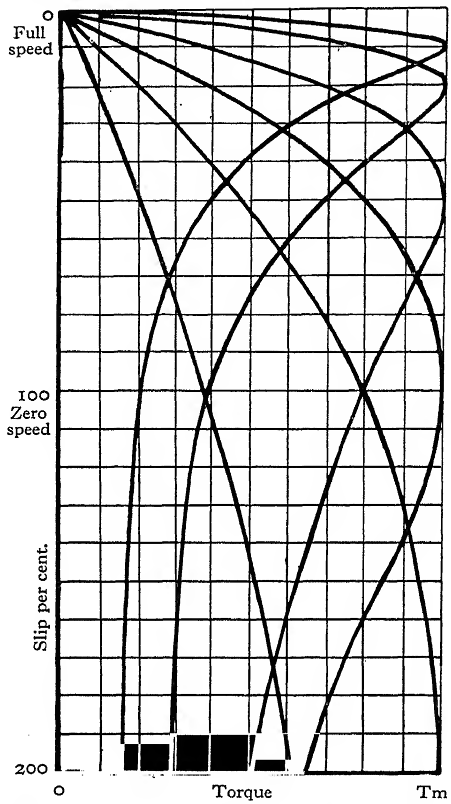



*Fig.* 9. Torque curves for three-phase slip-ring induction motor, for a speed range from normal full speed to a negative (braking) speed of −100 per cent.

This resistance is cut into wound rotor circuit by means of external resistors connected at the slip-rings, and cut out when full speed is reached; but in the case of the plain squirrel-cage rotor such resistance would have to be permanently in circuit, causing heating and a loss of efficiency when the motor is running. It should be borne in mind that many squirrel-cage models advertised to have an extra high starting torque possess the latter defect. Curves showing the variation of torque over the whole speed range for rotor circuits possessing varying amounts of resistance are given for both polyphase and single-phase motors in Figs. 9 and 10.

These curves show that there is a given maximum torque for any induction motor at a given voltage, averaging about twice the normal full-load value at rated potential, and occurring, with a low resistance rotor alone in circuit, at about nine-tenths of synchronous speed. By the insertion of resistance the maximum torque can be made to take effect at lower speeds, while a certain value, which may be obtained from

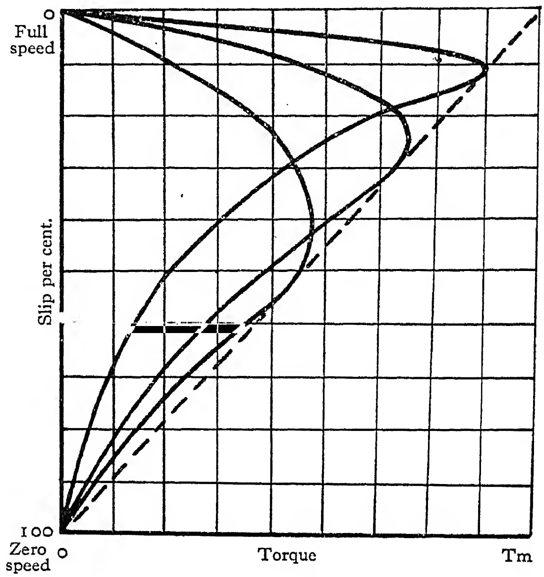



*Fig.* 10. Torque curves for single-phase slip-ring induction motor.

the diagram, will give maximum torque at starting. The use of a series of resistance steps is to change the position of maximum torque as the motor speeds up. Under any given conditions the torque is proportional to the square of the voltage.

The prolongations of the curves in the lower half of Fig. 9 indicate the negative torque developed when the stator connexions are reversed by the change over of two leads. The action is the basis of braking by ' plugging ', and the curves show the amount of resistance suitable for this purpose.

A method of obtaining a high-resistance rotor for starting purposes only, without the use of slip-rings, and without departing from the squirrel-cage form, is that due to Boucherot and indicated in Fig. 11. It is known that the inductance of a winding is much increased by deepening the slots in which it is accommodated. If therefore a low-resistance set of conductors is located at the bottom of deep slots and a high-resistance set above them (the so-called ' double-deck ' winding), the high reactance of the former at standstill, when the rotor frequency

is a maximum, will prevent any great amount of current from flowing through them. The reactance of the high-resistance circuit, however, is low, and this one comes into action and gives a high starting torque. As the rotor speeds up its frequency decreases, and more and more current flows through the deep winding Finally, at full speed both sets of conductors are working in parallel. Machines with such rotors stall (i.e. stop under load) at a slightly smaller load than those with the single winding, but the superior starting torque more than compensates for this defect.

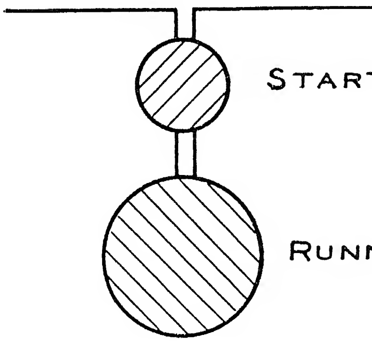



*Fig.* 11. Section of 'double-deck' slot for Boucherot winding.

¶ LOAD CURRENTS OF INDUCTION MOTORS.—The principal motor data required in the design of control gear are the normal full-load currents for the various sizes. These are given by the following formula:

$$\text{Current per phase} = \frac{H.P. \times 746}{n \times V \times \eta \times P.F.},$$

where $n$ = 1 for single-phase motors,
$\sqrt{2}$ for two-phase motors,
and $\sqrt{3}$ for three-phase motors;
$V$ = voltage between phases,
$\eta$ = efficiency,
$P.F.$ = power factor.

If the two last are expressed as a percentage the numerator must be multiplied by 100 in either case. As a rough guide to the efficiency it may be mentioned that the figures for a 5 H.P. and a 100 H.P. polyphase machine are about 80 and 90 per cent. respectively, or 75 and 85 per cent. for single-phase. The power factor averages 85 per cent. at normal full load for polyphase and 82 per cent. for single-phase motors. The actual currents, however, may be obtained from the accompanying table for the ratings most frequently employed.

¶ SPEED ADJUSTMENT OF INDUCTION MOTORS.—The principles discussed above will have shown that the induction motor is essentially a constant-speed machine. Just as the speed of the D.C. shunt motor may be

varied by means of armature resistance, so that of the induction type may be modified by rotor resistance, the process being an equally wasteful one in both cases. The curves in Figs. 9 and 10 will give the characteristics of this method of adjustment, showing *inter alia* that the speed with any given resistance is not constant, but varies with the applied torque.

TABLE 2. NORMAL FULL-LOAD STATOR CURRENTS FOR THREE-PHASE INDUCTION MOTORS

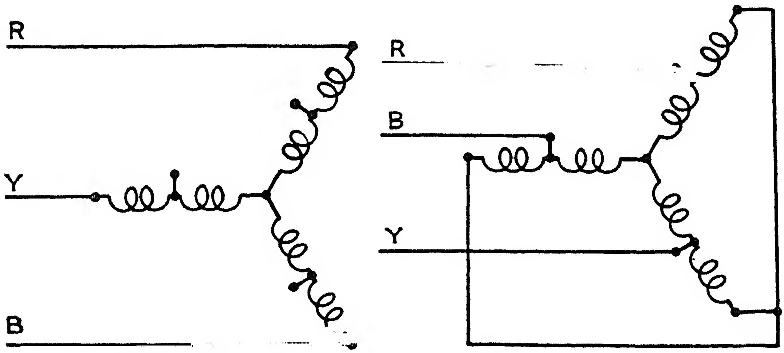
| *Size of Motor B.H.P.* | *Voltage.* 220. | 400. | 440. | 500. | 3,000. |
|---|---|---|---|---|---|
| ½ | 2·6 | 1·4 | 1·3 | 1·1 | — |
| 1 | 4 | 2·5 | 2 | 1·8 | — |
| 2 | 7 | 4 | 3·5 | 3 | — |
| 3 | 10 | 5·5 | 5 | 4·5 | — |
| 4 | 13 | 7 | 6·5 | 6 | — |
| 5 | 16 | 9 | 8 | 7 | — |
| 7·5 | 23 | 12 | 11 | 10 | — |
| 10 | 30 | 16 | 15 | 13 | — |
| 12·5 | 37 | 20 | 18 | 16 | — |
| 15 | 44 | 24 | 22 | 19 | — |
| 20 | 57 | 31 | 28 | 25 | — |
| 25 | 70 | 38 | 35 | 31 | — |
| 30 | 81 | 45 | 41 | 36 | — |
| 35 | 93 | 51 | 46 | 41 | — |
| 40 | 107 | 58 | 53 | 47 | — |
| 45 | 118 | 64 | 59 | 52 | — |
| 50 | 132 | 73 | 66 | 58 | — |
| 75 | 191 | 105 | 96 | 85 | — |
| 100 | 255 | 140 | 128 | 112 | 19 |
| 125 | 312 | 172 | 156 | 138 | 23 |
| 150 | 368 | 203 | 184 | 163 | 27 |
| 175 | 424 | 234 | 212 | 187 | 31 |
| 200 | 480 | 265 | 240 | 211 | 35 |
| 225 | 540 | 297 | 270 | 236 | 40 |
| 250 | 599 | 330 | 300 | 263 | 44 |
| 300 | 720 | 396 | 360 | 317 | 53 |
| 350 | 837 | 460 | 419 | 369 | 62 |
| 400 | 952 | 523 | 476 | 418 | 70 |
| 500 | 1,170 | 644 | 585 | 514 | 86 |
| 600 | 1,405 | 774 | 703 | 619 | 103 |
| 800 | 1,873 | 1,030 | 937 | 823 | 137 |
| 1,000 | 2,315 | 1,275 | 1,157 | 1,020 | 170 |

The same caution should be observed in the use of the above table as was mentioned in connexion with D.C. motors on p. 13 of the last chapter.

There is unfortunately no method of speed adjustment corresponding to the field regulation of a D.C. machine, and mechanical change-speed gearing is in consequence more frequently required with A.C. than with D.C. motors. There are, however, other methods available in the A.C. case, none of which possess at the same time both the convenience and the efficiency of field variation. The simplest is the reduction of the stator voltage, either by series resistance or reactance or by a reducing

transformer; but this is very inefficient and is chiefly used for small motors such as those driving fans. A second method consists of changing the number of poles on stator and rotor simultaneously, and a third employs two motors connected in cascade, i.e. the wound rotor of the first supplies the stator of the second. These are both more efficient than the voltage method, but are very expensive.

A short description of one pole-changing method will be given, as it is of some importance in connexion with the operation of lifts, enabling regenerative braking to be obtained at partial speeds with squirrel-cage motors, as described in Chap. XVII. When it is required to provide a half speed by doubling the number of poles, the one winding is used for both, but each phase is divided by medial tappings in order that the coils may be regrouped as shown in Fig. 12. But when




*a.* Full speed. *b.* Half speed.

*Fig.* 12. Speed regulation of induction motor by doubling the number of poles. Note change-over of main leads to secure same direction of running.

other speed ratios are desired, such as 3 : 1 or 5 : 1, entirely separate windings are provided. Another alternative consists of a series-mesh and parallel-star transformation.[1]

¶ ADVANTAGES OF THE INDUCTION MOTOR.—As compared with D.C. motors the induction type is smaller, cheaper, and more robust. The absence of a commutator is a particularly valuable feature; and in the squirrel-cage form the impossibility of damaging the rotor by overheating or short-circuiting makes for long life and reliability.

It suffers in the comparison through the lack of convenient speed-control, the difficulty of braking by the dynamic method, a somewhat lower efficiency, and a smaller short-time overload capacity. Its starting torque is also not so effective as that of the D.C. series motor.

As compared with the synchronous motor it has all the above advantages, and possesses in addition excellent starting and accelerating qualities that are non-existent in the latter type. Its power factor is

[1] See Kincaid, 'Change-Speed Induction Motors', *Electric Journal*, 1924, vol. xxi, p. 357.

however comparatively low, especially in the smaller sizes and slower speeds, and at light loads. For example, the average power factor of a 10 H.P. fully loaded induction motor is about 80 per cent., and about 90 per cent. for an average 1,000 H.P. example. At half, quarter, and no load the value reduces to about 0·85, 0·58, and 0·1 respectively of the full-load figure.

¶ THE CIRCLE DIAGRAM.—A number of induction motor problems, including many concerned with control gear, are very easily solved by means of the circle diagram, and a brief description of this is therefore appropriate. If the voltage and current in a given motor are plotted vectorially, and the current modified to represent various loading conditions, it is found that the end of the current vector moves in the arc of a circle, enabling its magnitude and phase-angle to be predicted. This is indicated in Fig. 13.

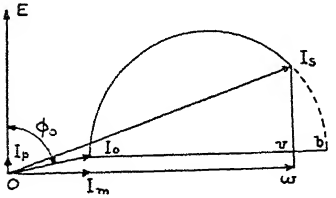



*Fig.* 13. Evolution of circle diagram.

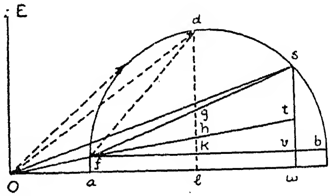



*Fig.* 14. Complete circle diagram.

Here $OE$ represents the applied voltage, and $OI_0$ the no-load current to any convenient scale. This current is never less than about 25 per cent. of normal full-load value, and is even more if the air-gap is not reduced to the minimum practicable. It is the resultant of the power component $OI_p$, which is used up in overcoming the no-load copper loss, the iron loss, and that due to friction and windage, and the 'magnetizing' component $OI_m$ which increases approximately with the air-gap. All these can be regarded as constant for all loads and speeds. Then when load is applied to the motor the end of the current vector always lies in the circular arc shown, which is fully defined as soon as one other point on the arc is ascertained, and is drawn about $I_0b$ as diameter. The highest value of the current is $OI_s$, being that flowing when the rotor is 'stalled', or brought to a standstill by an excessive overload. This is an easy value to obtain, and is therefore used as the second point in testing.

The diagram so constructed also gives the phase of the current, being the angle between the voltage and current vectors, and the power factor is the cosine of that angle. But many other values can be obtained by slightly elaborating the diagram and by simple measurement to scale. This is indicated in Fig. 14, in which the line *sv* has been divided at *t* so that *st* : *tv* :: copper losses in rotor : copper losses in stator. These are easily calculated as $I^2R$, all the figures being

known; and joining $s$ to $f$ completes the diagram. Then to find the electrical particulars at any other current represented by the vector $Od$, $df$ and the perpendicular $dghkl$ are drawn as before, and the following values are given:

$$
\begin{aligned}
dl &= \text{input (at stator)} \\
kl &= \text{constant losses} \\
hk &= \text{stator copper loss} \\
gh &= \text{rotor copper loss} \\
dg &= \text{load (rotor output)} \\
dh &= \text{torque} \\
\frac{dl}{Od} &= \text{power factor } (\cos\phi) \\
dl\ \frac{dg}{\cancel{Od}} &= \text{efficiency } \left(\frac{\text{output}}{\text{input}}\right) \\
\frac{hk}{dh} &= \text{slip.}
\end{aligned}
$$

The first six of these represent the power components of the various currents. They may be expressed in watts by multiplying by the voltage and the number of phases. The relative value of the torque $dh$ is a particularly useful quantity in control problems. As described, it is given in 'synchronous watts', and may be obtained in lb.-ft. by multiplying the rotor output in watts by $\left(\frac{7{\cdot}05}{\text{r.p.m.}}\right)$. The former rating in synchronous watts, i.e. the power that would be developed at synchronous speed, is the more convenient, however, and for this reason the more usual.

¶ SELF-STARTING SYNCHRONOUS MOTORS.—It can be stated that the principal advantages of the induction motor are evidenced when it is accelerating to full speed, and of the synchronous type when full speed has been attained. An important advance has been recently effected by designing and controlling the one machine in such a way that it constitutes these two types of motor in turn, and this is carried out in two ways. According to the first a salient pole synchronous machine is converted to a squirrel-cage motor; while for the second a slip-ring induction machine is converted to a synchronous motor at the conclusion of the starting period. Either transformation is rendered possible by the fact that the stator, which constitutes the armature of a synchronous machine, is to all intents and purposes identical with the stator of the induction type, and when supplied with a polyphase current at decreased voltage, obtained by means of a reducing transformer, it produces a rotating field as required by the latter machine. In the case of the ordinary synchronous motor, the addition of a short-circuited rotor winding to its revolving field magnet is all that is needed to endow the synchronous motor with the starting characteristics of the squirrel-cage machine.

Such a winding is actually fitted to the majority of synchronous

machines to obviate 'hunting' of the speed. If a sudden peak occurs in the load the rotor will be slightly retarded, and will not immediately resume its correct position in phase with the applied alternations. Instead, it will swing forward again, overshooting the mark after the manner of a pendulum, and the process will repeat itself over quite a long period. At each swing a cross-flux is caused to move over the pole-faces; the simplest method of damping out the phase-vibrations is to fit short-circuited conductors in transverse slots formed in the pole-pieces, which are cut by the cross-flux and thus generate eddy currents. Since the hunting is compelled to do work it is quickly brought to an end.

By taking advantage of this winding a starting torque equal to 50 per cent. of normal full-load value can easily be obtained, while more could be achieved if a double-deck winding were used such as has been described earlier. A wound-rotor arrangement would also of course be possible, but would render the rotor very complicated, and there seems no prospect at present of its coming into use. The squirrel-cage form, however, is being utilized to some extent for driving the main rolls in metal-mills. It offers the advantages of an increased efficiency, averaging about 2 per cent., and of a unity power factor as soon as the starting stage is past.

The conferring of synchronous characteristics upon a slip-ring induction motor is simply effected by supplying the rotor with D.C., causing it to function as a bipolar field magnet, and producing the so-called synchronous-induction motor. It is necessary to connect two of the brushes to form one pole of the D.C. circuit, the remaining brush constituting the other pole; so that two of the phase windings are paralleled and excited in series with the third.

The motor is first accelerated by means of the usual rotor resistance. After this is cut out a change-over switch is operated, which momentarily short-circuits the rotor and then connects the exciter in the manner indicated. Owing to the high slip-ring voltage induced at starting, large machines of this class are provided with six slip-rings, to enable the rotor windings to be connected in delta for starting and in star for running.

¶ Compensated Induction Motor.—It has been stated that the low power factor of the induction motor places it at a disadvantage as compared with the synchronous type. This drawback is removed in the various patterns of compensated slip-ring induction motor which incorporate a phase-advancing winding, enabling them to work at unity power factor. A commutator is a necessary complication of the combination.

One of the simplest forms is that designed by the General Electric Co., Ltd., in which a separate low-voltage winding on the rotor is commutated by means of three brushes, these being connected to the rotor slip-rings when acceleration is complete, by the same switch that disconnects the starting resistance. The control is therefore no less

simple than in the case of the ordinary induction machine. In addition, the ' pull-out ' torque is increased, and a considerable saving in running cost will ensue in the numerous districts where low power-factor is penalized.

¶ Mechanical Features.—The details given in the last chapter under the above heading apply equally to A.C. motors. In addition, it may be mentioned that roller bearings are particularly valuable with induction motors in minimizing wear, and thus enabling the air-gap to be shortened.

## IV

# MANUAL STARTERS AND CONTROLLERS

THE control of electric motors is effected by means of apparatus which can be broadly classified under the following headings: (1) face-plate type; (2) drum and finger type; (3) liquid type; (4) multiple-switch type; (5) contactor type.

The above are arranged roughly in the order of their invention. The third, which employs a liquid resistance and thus dispenses with special contacts, is on this account in a separate class from the others and will be dealt with in a special chapter. The first and second for a long time held the field between them, and even at the present day are employed for the great majority of ordinary small and moderate sized motors. Contactor gear is the basis of the automatic and large-power controllers that have done so much to extend the utility of the electric motor in exacting situations and heavy industries. Between the first two and the contactor types a number of what may be called transitional patterns have been developed, which have endowed manual gear with varying degrees of automatic regulation. To this class the multiple-switch type may be said to belong, as well as variants of the face-plate and drum starters and controllers. It is the purpose of this chapter to deal with the first two and the transitional apparatus, leaving automatic control proper for separate description.

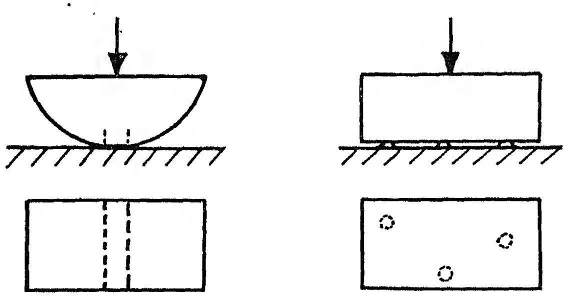
It must be first emphasized that although the form of control apparatus may be modified, the root principles upon which it works are unchanged. A full understanding of the design of manual control gear will therefore materially assist in the comprehending of the more elaborate equipments to be described later. It will thus be specially advantageous to begin with the first principles of the subject, and to show how the utility of the various types is derived.

All control gear depends for its action upon the making and breaking of electric circuits, whether for the purpose of cutting out or inserting resistance, or of altering the relationship of the windings or other components involved. The efficient making of a circuit involves the conduction of the current from one contact to the other with not more than the permissible heating and voltage drop. Satisfactory conductivity depends upon the effective area of the surfaces in contact, and the pressure between them. Breaking the circuit, on the other hand, involves the separation of the contacts without appreciable burning, fouling, or melting of the surfaces.

It will not be difficult to realize that the whole of the opposing areas are not always in effective contact. Indeed, a comparatively small particle of dirt may separate them completely, while a similar small particle or projection of conducting material will restrict the effective

contact surface to the face of the particle itself. Nominally flat contacts are very seldom accurately so, and nearly always touch only at a few projecting spots. It is for these reasons that contacts are designed wherever possible to engage with a rubbing motion, which has the effect of cleaning and truing the surfaces. The advantages of the widely adopted line-contact principle also follow, and are made clear by the illustration in Fig. 15. By means of the pressure against the curved surface of A complete contact along a definite strip is secured, due to the temporary flattening of the metal along this area. Practical experience has shown this form to be much more efficient than the flat contact, indicated at B, and the former is adopted for practically all drum switches, contactors, and oil switches.

The breaking of a circuit without serious arcing may be a much more troublesome problem, the difficulty of which increases with the voltage



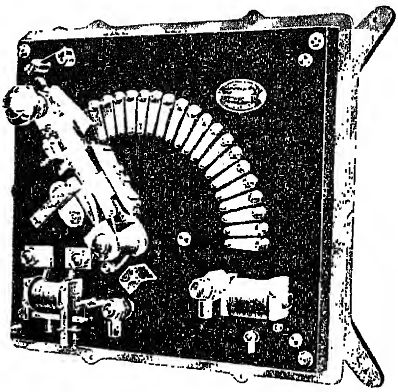
A B

*Fig.* 15. The effectiveness of a line contact (A) compared with a face or butt contact (B), showing in an exaggerated form the relative areas of true contact.

and the current in the circuit. No special means are ordinarily required, for example, in breaking a current of less than an ampere at voltages up to about 500, or quite large currents at voltages below about 16, but when the current in the former case or the potential in the latter exceeds the values given the design must be modified accordingly. As far as possible the endeavour is made to restrict the breaking of the circuit to certain contacts, in which burning at the current-carrying surfaces is minimized by one of the following expedients: (1) quick break; (2) auxiliary 'arcing' contacts; (3) magnetic blow-out; (4) oil immersion.

Of these the first limits the duration of the arc, while the second transfers it to special surfaces, often of carbon, which are not engaged in the full 'on' position. The third forces the arc rapidly in a direction perpendicular to its length as though it were an armature conductor of a motor; thus it is very quickly extended and broken. The fourth quenches the arc, and in the case of alternating currents prevents it from re-forming.

¶ FACE-PLATE TYPE.—In the first arrangement of contacts for a rheostat, a single moving member is passed over a row of fixed studs attached to an insulating support, and arranged at such intervals that the moving surface does not leave any one stud before it touches the succeeding one. This method is the simplest possible way of making a series of connexions. The surfaces are kept in good condition by rubbing, and a considerable degree of pressure is maintained between them without requiring the external application of a corresponding force in moving the arm. Now when resistance is being cut out the circuit is not broken at any of the studs, and hence the type is especially suited for starters, with which stoppage is effected by opening a special switch. For rheostats intended to be left with portions of the resistance in circuit continuously the arm may have to be moved in either direction; and since a certain amount of voltage will have to be broken at any of the studs their number is made large enough to reduce this difference of potential to as small a value as possible, such as 16 to 50 volts, depending on the current passing. An advantage of the face-plate design is that it is a simple matter to provide a large number of contacts. When used as a starter it is fitted with from about seven to fifteen; but for use as a controller or a field regulator it may have as many as fifty, or even more.

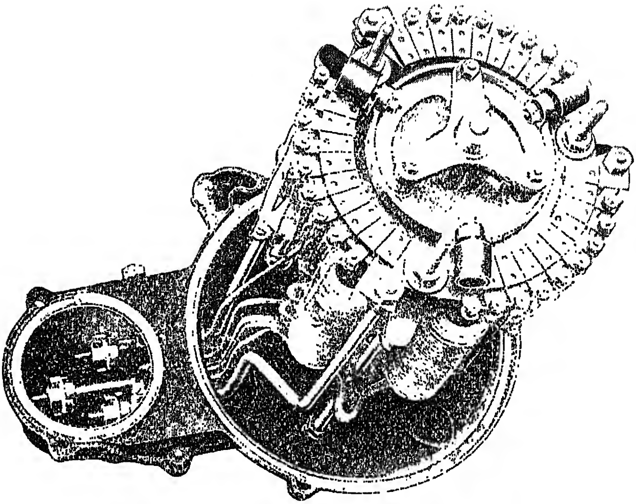


*Veritys Ltd.*

*Fig.* 16. High-capacity face-plate starter with arcing contact and overload release.

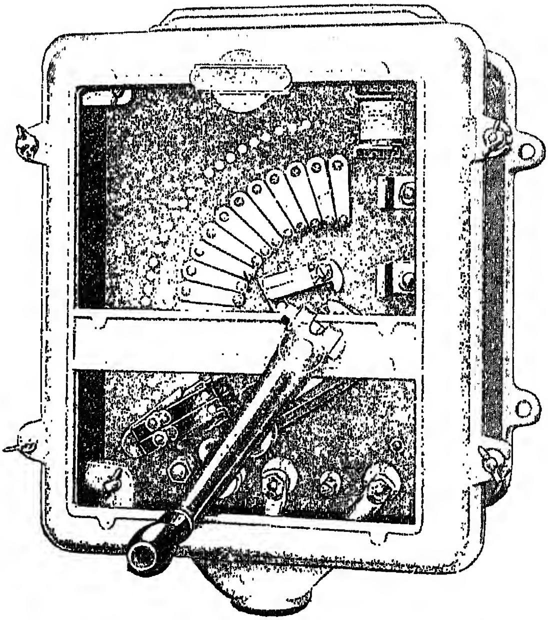
A heavy-duty pattern is shown in Fig. 16, in which there are special laminated contacts for taking the current on the final step, the only one which is in use continuously. There is also an auxiliary contact of carbon above the main studs for drawing off any arc that may be formed by backing the arm during the starting process. The design and location of the no-volt and overload releases can be incidentally made out from this illustration. The studs are designed quite simply for renewal from the front. In spite of its capacity—this model is intended for use with a 50 H.P. motor—the apparatus is seen to be quite compact, although the resistance is contained in the case behind the contacts. Of all rheostats it is the best adapted for panel or wall-mounting.

A columnar form of face-plate starter, in which both resistors and face-plate are oil-immersed, is shown in Fig. 17. In this case the contacts are located at the bottom of the drum; and the moving element is in the form of a roller, which may be regarded as presenting an extreme form of line-contact. The illustration is further interesting in that it shows a three-phase pattern, there being three moving contacts and three sets of studs.



*George Ellison.*

*Fig.* 17. Oil-cooled rotor starter, removed from tank and inverted, to show face-plate with flat contact studs and roller moving contacts.



*Igranic Electric Co., Ltd.*

*Fig.* 18. Combined face-plate starter and shunt regulator showing small interlocking switch, operated by starter arm, to ensure full field for starting.

With regard to the design of contacts, the studs for the smaller sizes are flat circular disks provided with threaded stems that pass through the slate, and are held by nuts at the back, between which the connecting wires are clamped. It is usual to fit either three nuts per stem, or two with a locking washer. The following figures indicate approximately the current-carrying ability of round studs, both for starting and continuous duty:

TABLE 3. CURRENT-CARRYING CAPACITY OF ROUND STUDS

| *Diameter of Contact. Inches.* | *Current—Amperes.* *Starter Duty.* | *Continuous Duty.* |
|---|---|---|
| $\frac{3}{8}$ | 30 | 20 |
| $\frac{1}{2}$ | 50 | 30 |
| $\frac{5}{8}$ | 100 | 50 |
| $\frac{3}{4}$ | — | 100 |

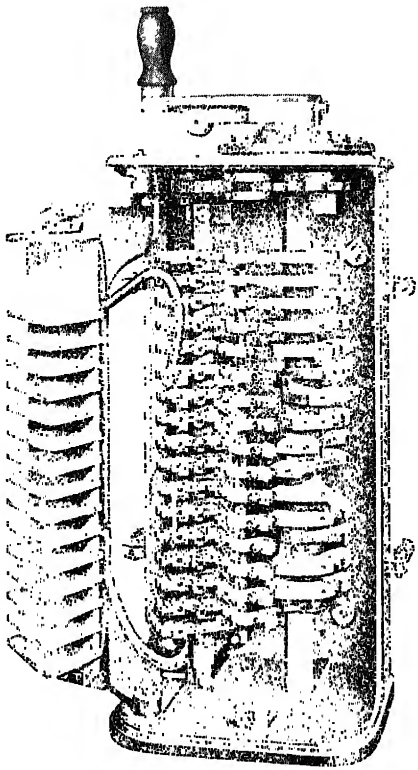
For currents above about 100 amperes flat elongated contacts are used, which are usually attached to brass studs in the slate by countersunk screws. Care is taken that the leading edge of the moving element makes simultaneous contact along its whole length with the front edge of the stud. A common figure for the current density in the case of starting duty is 160 amperes per square inch.

The moving contact usually consists of a flexibly supported brass shoe that is pressed on to the studs by means of direct-acting helical springs. For small models a tongue of spring brass is often used, which may be extended to encircle the central pivot. In any case efficient contact must be provided at the pivot end as well as between the shoe and the pivot.

The limitations of the face-plate pattern have already been largely indicated. It is not adapted to withstand rough, frequent, or careless usage, being susceptible to damage by arcing and not being very robust mechanically. It is also capable of giving effect to only the simplest of operations, its use as a single-arm model being practically confined to plain starting or controlling. Fitted with a second arm it is, however, sometimes employed for field regulation in addition, as exemplified in Fig. 18. In such a model it is important to provide against the possibility of starting up with any of the field resistance in circuit. In this particular example the handle is attached to the regulator arm, and by its means both arms are moved for starting up until the no-volt release retains the starter arm. The regulator contact is then moved in the reverse direction, cutting resistance into the field. Upon failure of the voltage or opening of the main switch both are forced by the spring to the 'off' position.

¶ THE DRUM TYPE.—For heavy currents and frequent duty, especially where the handle is to be moved in both directions without relying upon a switch for breaking the circuit, a drum type is employed, such as that shown in Fig. 19. In this not only is the whole mechanical design more robust and more perfectly enclosed and protected, but a

separate pair of substantial contacts is provided for each switching operation, breaking circuit within insulating and fire-resisting arc cheeks, and nearly always under the influence of a strong magnetic blow-out. At one time an actual wooden drum was employed, to which the contact segments of strip copper were screwed. Nowadays the whole construction is incombustible, the moving contacts being typically supported by



*Metropolitan-Vickers Electrical Co., Ltd.*

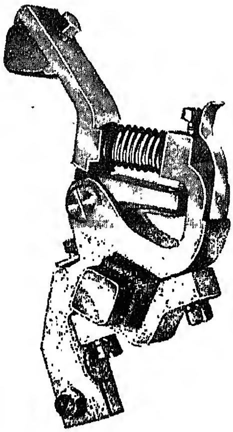
*Fig.* 19. Drum controller, showing blow-out coil and arc shield swung clear.

cast-iron sectors bolted to the mica-insulated operating shaft, which is usually of square section. The fixed contact fingers are clamped to one or more fixed bars, also insulated with mica. The resistance is mounted in the drum casing for small sizes only.

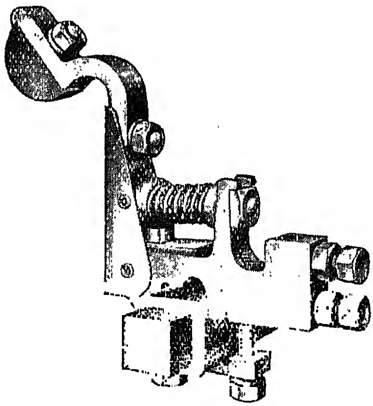
By this apparatus any scheme of operation, however elaborate, may be carried out, a familiar instance being the series-parallel and braking controllers used on electric tram-cars, the scheme for which is given in Chap. VI. Connexions for both forward and reverse running are

made when desired by means of a single drum, there being a double set of either fingers or drum-sectors. The former method would necessitate two finger bars; and, where a magnetic blow-out is fitted, it is usually simpler to duplicate the sectors.

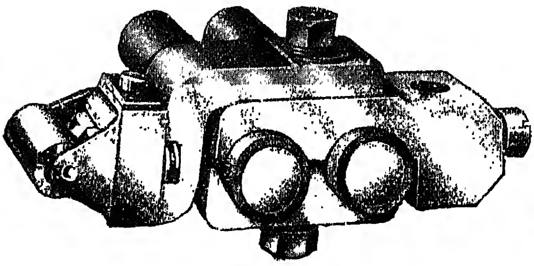
The design of both fingers and cylinder is directed towards the easy replacement of current-carrying parts that are subject to wear. Sim-



*British Thomson-Houston Co., Ltd.*



*Metropolitan-Vickers Electrical Co., Ltd.*



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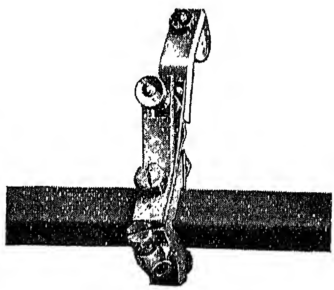


*General Electric Co., Ltd.*

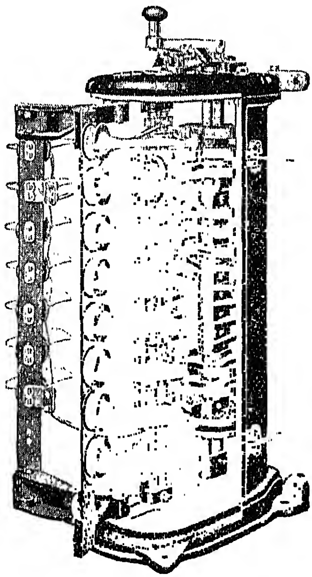
*Fig.* 20. Typical designs of contact finger.

plicity and robustness are highly desirable qualities, and ingenuity devoted to securing these ends is well spent.

Typical designs of finger are shown in Fig. 20, in all of which the easy removal and refitting of the tip should be observed. Reliance is not placed upon a pivot for conducting the current, any such joint being shunted by a flexible connexion. Each finger is kept under a carefully regulated pressure imposed by the spring seen in the figures, the forward movement being limited by an adjustable stop so that it is only

raised by a slight amount when the sector passes under it. The spring pressures vary from about $3\frac{1}{2}$ lb. for a tip $\frac{1}{2}$ in. wide to 15 lb. for a 1 in. tip. A further design of finger is shown in Fig. 110, which is very cheaply pressed out of mild steel strip, and is mounted on a duplex finger bar. It is especially suitable for small horizontal drums.

It is in the design of the supports for the sectors of the cylinder that the greatest saving can be made, when the scheme is carefully thought out. Each casting, being clamped on to a square rod covered with micanite or bakelite, is initially insulated from its fellows, and the sectors are electrically joined as desired by copper straps. It frequently happens that sectors on opposite sides of the cylinder have to be insulated from each other, and this is usually accomplished by supporting at least one of them on a short cantilever projecting from the adjacent sector casting. Considerable economy in machining costs is possible by designing and manufacturing the parts to secure interchangeability, the contact surfaces having the correct radius and curvature to within a few thousandths when simply clamped in position. When this can be attained, the final skimming of the complete cylinder in the lathe is obviated.



*George Ellison.*

*Fig.* 21. Drum controller with individual blow-out coils, giving an outward movement to the arc.

A star-wheel and roller-pawl are fitted to the drum-shaft at one end in order to make the contacts register correctly and to indicate to the operator when they are coming together. The more definite pawl-type step-by-step device described later is also applicable in some cases.

The magnetic blow-out consists of a strong flux generated by a coil usually connected in series with the load current. In the form shown in Fig. 19 the iron supports for the sectors form one pole for the flux, while the other is formed by a hinged fitting that not only constitutes an iron circuit and pole-piece for each pair of contacts, but also supports arc barriers of asbestos material effectively separating adjacent sectors. Since the flux is radial, the arc, being drawn out in a tangential direction, is moved axially against the barriers, as will be indicated if Fleming's ' hand ' rule be applied. The extinguishing process is thus one of cooling rather than elongation.

A second pattern of blow-out is employed in the controller shown in Fig. 21. There is now a separate blow-out coil surrounding the base of each iron-cored arc shield ; and since these are wound alternately

right- and left-handed, the shields are made alternately north and sou poles. Thus the flux passes transversely across the arc chute, and t arc is in consequence driven outwards, and not against one or oth side of the chute. A more reliable blow-out is the result, there bei practically no tendency to heat the arc shields as with the previous for

Drum-controller diagrams are represented as though the peripher surface were rolled out flat, or 'developed'. Fingers are indicated small disks, and sectors by horizontal bands. When the sectors a electrically connected, this is indicated by vertical bands betwe them. For the sake of clearness the external apparatus connect to the fingers, such as resistors, switches, field coils and armature, a

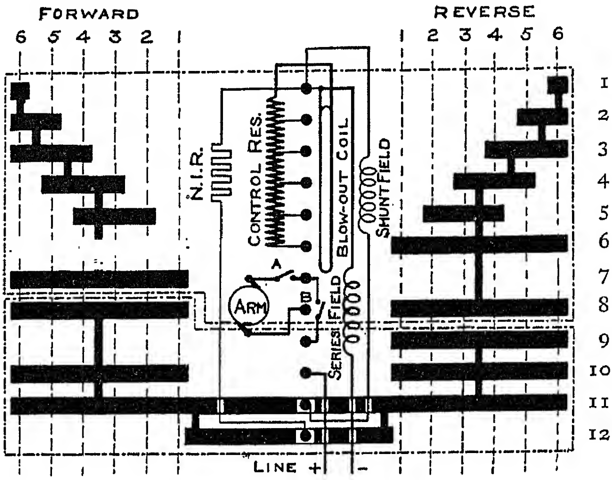



*Fig.* 22. Drum reversing controller for D.C. compound motor, suitable also for shunt or series types.

usually shown on a much reduced scale as though located at the finge to which they are joined. The successive positions of the fingers up the sectors at the various steps are indicated by numbered vertical line

In order to illustrate the principles of the drum controller tw typical examples will be described, while others will be detailed und their appropriate headings in later chapters. It will be sufficient he if a D.C. and an A.C. pattern be specially dealt with. Both are show as reversing models, but may be converted to non-reversing by th omission of either the right- or the left-hand sets of drum sectors an all but one or two of the lower group.

The first diagram, Fig. 22, may be employed as a general scheme f the plain series resistance control of a D.C. motor. Actually the latt is shown as a compound model, but the series and shunt cases may b deduced by the omission of one or other of the field windings an connexions. As usual, the fingers are shown as black disks in th

middle, while the cylinder is developed on the left and right of these for forward and reverse running respectively. On studying the vertical connecting strips between the sectors it will be seen that the whole cylinder, including both left and right halves, is divided electrically into two portions, an upper and a lower, which are insulated from each other. For special clearness these are enclosed in two dotted 'frames' in this figure.

First, the negative main goes to the top finger, passing through the series field on its way. The latter is then always alive, and two extra fingers and sectors must be added if it is desired to disconnect it at the controller; a complication that is, however, seldom employed except in

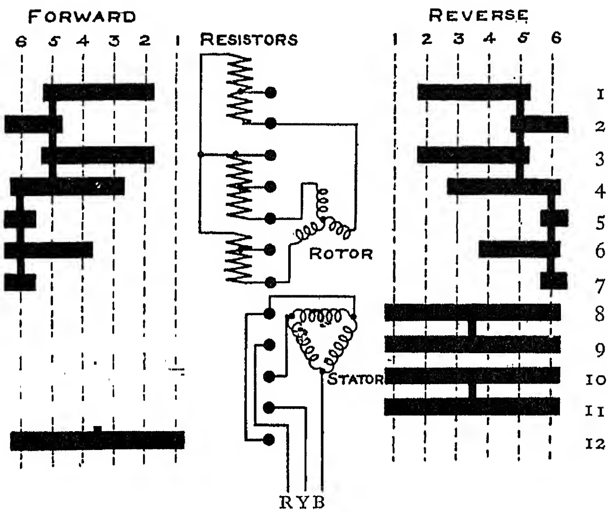


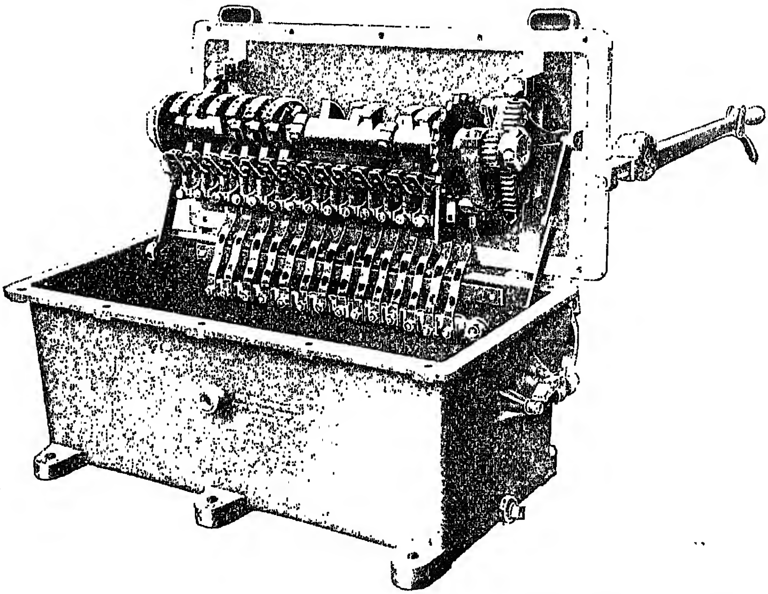

*Fig.* 23. Drum reversing controller for wound-rotor induction motor, with six steps of acceleration.

colliery and steelworks practice. The controlling resistance is distributed among the six top fingers, the series blow-out coil being included in with the last step, so that it also is cut out when acceleration is complete. Thus the upper section of the cylinder is made negative, through the resistance, as soon as finger 6 meets the sector on either side. Successive steps of resistance are then short-circuited as the drum is turned. The bottom sector of the section on either side connects the negative line to the upper or the lower armature terminal, depending on which half of the cylinder comes into play.

Coming now to the lower section of the cylinder, the two top sectors on each side join the remaining armature terminal to the positive main, the latter going to finger 10. Reversal is thus brought about by changing over the armature connexions. The two bottom sectors are for switching in and out the shunt field and the non-inductive resistor

respectively, the latter being shunted across the field terminals just before the former is cut off from the line, to act as a 'discharge' resistance. These sectors, together with fingers 11 and 12, are omitted for series motors. The positions for a limit switch or switches are indicated at *A* and *B*, the latter being only in operation during the reverse motion.

When an A.C. motor is concerned three insulated cylinder sections are required, as shown in Fig. 23. Of these the uppermost is solely concerned with the progressive short-circuiting of the rotor resistance,



*British Thomson-Houston Co., Ltd.*

*Fig.* 24. Typical oil-immersed controller with hinged cover, showing flexible connexions to fingers. Capacity: 50 H.P. at 650 volts.

while the two lower bring about reversal by changing over the *R* and *Y* connexions to the stator, these lines going to fingers 9 and 11 respectively. It will be observed that the *B* line is left connected to the stator, and two further fingers and sectors would be needed to isolate the motor completely.

Six steps of acceleration are obtained by cutting out resistance from one phase at a time, as described on p. 63 of the next chapter. Although it is a simple matter to remove equal amounts of resistance from all three phases at every step with a face-plate starter, such a practice would demand too many fingers and sectors for the drum type, and the unbalanced method previously referred to is nearly always used.

Such a controller as this, designed for oil-immersion with a horizontal

cylinder, is shown in Fig. 24. No magnetic blow-out is required, and the motion is derived from a long vertical lever through the medium of multiplying spur gearing. To facilitate inspection the complete drum mechanism may be removed by opening the lid on its hinges, the flexible strap connexions permitting this to be done without disconnecting the fingers.

There are other mechanical arrangements of the operating levers, while double-drum patterns are frequently employed. Further reference to these will be made in later chapters.

¶ CAM-TYPE CONTROLLERS.—A more robust type of drum controller has recently come into use, the contacts of which are identical with those of the contactor. The arrangement is exemplified in Fig. 25, in which there is a cam shaft rotated by the control handle and a single line of moving contacts engaging with a further line of fixed and rigid contact fingers. Each of the moving elements of this design consists of a lever with the horn-shaped contact supported upon a spring-operated knuckle joint at one end, and a roller upon an extension beyond the pivot at the other, with which the cam engages. Similar horn contacts are fitted to the fixed elements, and each pair comes together with a combined rolling and rubbing action, the contact being first established at the tip and then transferred to the lower part of the surfaces for the final and continued passage of the current. This principle ensures that any results of arcing expend themselves well away from the permanent contact surfaces; it has been found most effective in contactor design. Each pair of contacts requiring a magnetic blow-out is equipped with one of an individual series type exactly resembling that employed with contactors, and possessing the superior rupturing power of that type.

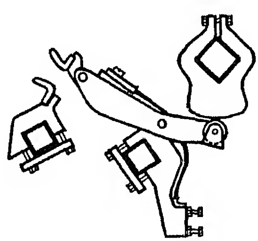


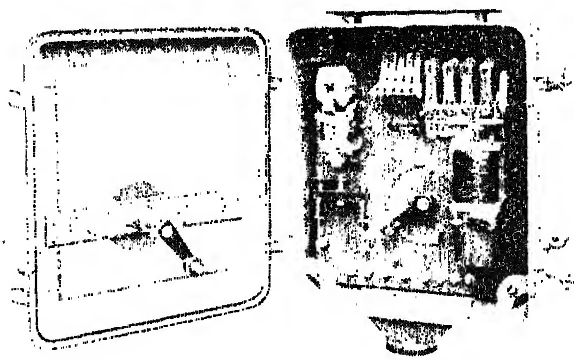
*Fig.* 25. Section across cam-type controller.

It will be observed that the pattern in the figure has its contacts opened by the cam, but they are closed, when released through the rotation of the latter, by a compression spring that is not visible in the figure. Most forms, however, operate upon the opposite principle, in that they are closed by the cam and thus dispense with the operating springs. The method shown has the advantage that, if a pair of contacts 'freeze' through a very heavy overload, they may be forcibly parted by means of the operating handle.

In addition to the greater general effectiveness of the cam type of controller, which renders it applicable for service too severe for the ordinary drum pattern, but not such as to require the use of full magnetic contactors, several other advantages should be noted. It is actually somewhat lighter than the usual type. Opening and closing are much quicker and it is almost impossible to hold the contacts in the 'just

touching' position. Owing to the complete independence of the different pairs of contacts, the design lends itself to unit construction, a given stock model being easily modified to give various combinations of functions. The greatest advantage, however, is the definiteness of making and breaking the circuit, due to the efficiency of the rolling contact and the contactor type of blow-out.

¶ AUTOMATIC DEVELOPMENTS OF MANUAL CONTROL GEAR.—The principal developments of the ordinary manual rheostat, in the direction of conferring upon it more or less automatic characteristics, are as follows : (1) time-element face-plate or drum-type models employing a dash-pot, pilot motor, or similar device ; (2) current-limit delays ; (3) step-by-step devices ; (4) 'inching' attachments ; (5) multiple-switch starters.



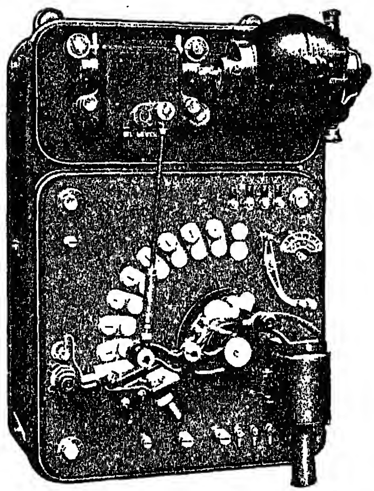
*Igranic Electric Co., Ltd.*

*Fig.* 26. Time-element starter set, solenoid type. See also Fig. 212.

¶ TIME-ELEMENT STARTERS.—The necessity of moving the arm of the ordinary face-plate starter through its appointed travel at the correct speed may become inconvenient for several reasons. In the first place it absorbs valuable time, ranging from about five to sixty seconds. Apart from the tedium of spending this time over the operation, there are occasions, such as the starting of an organ-blower, when the operator's attention is required elsewhere before the accelerating process is complete. Secondly, a motor has frequently to start work in the absence of an attendant at the moment when the need is felt, one of the commonest examples being the filling of a tank after the contents have fallen to a given level. Thirdly, remote control may be required, such as the starting up of a machine on one floor of a building from a location in another story. All these ends are served by a rheostat such as that in the right of the case shown in Fig. 26, the other components being a shunt regulator, starting switch, circuit-breaking contactor and shunt-resistance interlock. Upon the closing of the pilot circuit, the solenoid begins to lift the contact arm attached to its plunger, the movement being

regulated by the oil dash-pot below the arm. The latter is held at the end of its travel until the circuit is opened at the switch, when it is allowed to descend rapidly to the 'off' position ready for the next start. Since the pull becomes much greater as the plunger is sucked in, the dash-pot must be designed to offer an increasing opposition as the piston rises. This can be done by grading the cylinder bore, or by cutting a tapering groove in its wall, either of these permitting a varying oil leak to take place.

A somewhat more elaborate method, employed where great certainty and regularity of action are required, makes use of a small 'pilot' motor for actuating the moving contact. An example of this form is shown in Fig. 27, illustrating the use of worm reduction gear for producing slow motion. A limit switch is fitted to stop the motor when acceleration is complete, and a disengaging device to return the arm to the 'off' position when the voltage is interrupted.



*Electrical Apparatus Co., Ltd.*

*Fig.* 27. Automatic time-element starter, motor operated, for motors up to 15 H.P., with cover removed.

A variant of the cam-type of controller also comes within this classification. Instead of being contained in a 'drum' housing, the cam shaft and contacts are panel-mounted, and the former is rotated by a pilot-motor, by pneumatic power, or even by connexion to line-shafting. In this form it can accomplish the complicated sequences of operations of which the drum controller is capable, and approaches very nearly in its possible attainments to the full contactor type.

¶ Current-limit Delays.—Turning now to starters which are directly hand-operated, it is evident that the use of the starting resistance will be futile unless the arm is moved across the contacts at something approaching the designed speeds. A certain amount of experience and common sense is needed in the use of the ordinary pattern; in the hands of an ignorant or careless operator the starting resistance may afford no appreciable safeguard. For the benefit of such people a safety device is sometimes used, based upon the current-limit principle, in which a series coil carrying the full armature current brings about the locking of the starter handle when the current is above normal. When the current falls to the safe value, the handle is unlocked. Thus it is rendered impossible to cut out the resistance too rapidly.

The accompanying illustration, Fig. 28, indicates the form that such

a device might take, being in this case an extension of the function of the usual overload release gear. In addition to short-circuiting the low-volt coil, the armature is extended and provided with one or more teeth, which are able to engage with the corresponding teeth on the sector attached to the contact arm, and so arrest its forward movement. It is found possible to design this mechanism with sufficient promptness of movement to stop the arm if it is moved rapidly by the operator across the studs without any attempt to pause on his part.

¶ STEP-BY-STEP DEVICES.—A somewhat similar end is attained in another manner by what are popularly termed ' step-by-step ', or ' slow

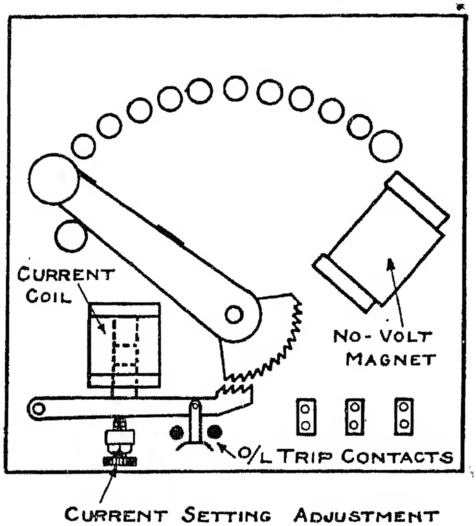



*Fig.* 28. Current-limit detent device applied to face-plate starter, shown combined with overload release.

motion ' devices, in which the arm is compelled to pause on every contact. A simple method designed by the author, involving only a trifling addition to the standard design, is shown in Fig. 29A. A pawl, fitted with two pallets that are approximately at right angles to each other, engages with a row of stout pins corresponding to the contact studs upon which the moving contact is required to pause. The forward motion is arrested when the arm is exactly over each stud, through the radial pallet striking the appropriate pin. The pressure on the handle must now be slightly relaxed, when the pawl will rotate under the influence of a spring until the tangential pallet strikes the next pin. The impediment is thereby removed and transferred to the next step, and so on. Where there is only one pause to be made, as with auto-transformer starters, the arrangement may be inverted, the pin being located on the arm and the pawl on the framework, as in Fig. 29B.

Another method, due to the Electrical Apparatus Co., employs a fixed zigzag track, in which a pivoted pin is compelled to travel, the pin being arrested at each of the corners where the track turns at right angles to the movement of the arm.

Such mechanisms are of special utility when the actual contacts are out of sight, such as in many pillar-type starters and in oil-immersed apparatus, since they enable the unseen contacts to be halted in exact registration. In the latter case the step-by-step devices are usually fitted to the back of the cover.

¶ INCHING DEVICES.—It sometimes happens that the moving arm of a face-plate starter is moved backwards, away from the stud with which it has just made contact. This may either be due to carelessness or nervousness, giving rise to unsteady operation; or it may be

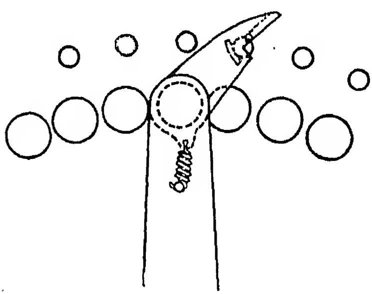
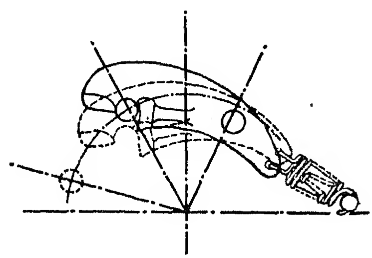


*Fig.* 29 A. Step-by-step device as applied to face-plate starters.



*General Electric Co., Ltd.*

*Fig.* 29 B. Same device as applied to A.C. drum controllers. The dotted lines show normal pattern of pawl: the full lines the position at moment of checking.

done purposely, through the motor being required to make only a few turns, the handle being moved on to the first or second stud only, and then released. In either case an arc would be set up between the fixed and moving contacts of an ordinary starter, resulting in serious burning.

Now inching, as the latter type of operation is called, is required for a number of industrial purposes, of which printing presses and rubber calenders are examples. In these the rolls have to be turned slowly at the start while the material is being fed in. For large machines special systems of drive employing auxiliary motors or other devices, such as those described in Chap. XXII, are employed. For small installations, however, the cost of these refinements would be prohibitive, and a special type of starter has been produced which enables the circuit to be broken at any stud without the formation of an arc.

The principle of these 'inching starters' is the provision of a loose contact member associated with the usual arm, which either makes or unmakes a contact when the handle is backed by more than about $\frac{1}{32}$ in., thereby causing a circuit-breaker or contactor to open and

rupture the circuit before the starter contacts can part. The illustration forming Fig. 30 shows the author's design for accomplishing this, a comparatively light 'follower' arm being moved by the main contact arm and handle, the mechanical contact between the two completing the electrical circuit energizing a contactor carrying the main current. A backward movement of the arm leaves the 'follower' behind by a fraction of an inch, and the contact is broken. An auxiliary fixed

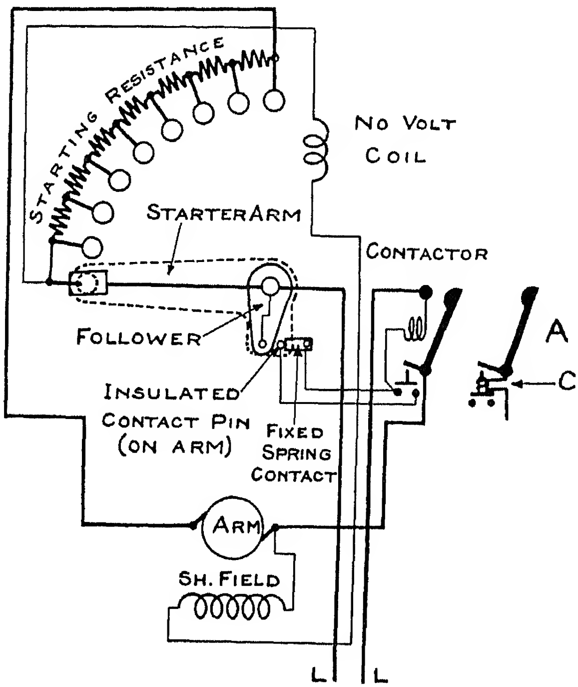


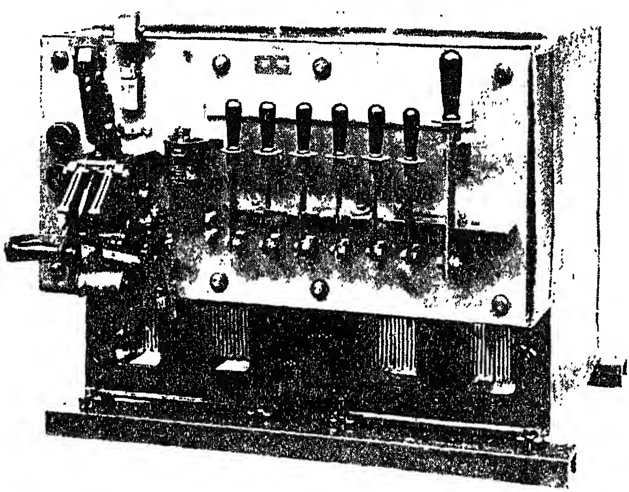

*Fig.* 30. Inching face-plate starter, with contact arm dotted. Addition to provide overload protection is indicated at *C* in Diagram A.

spring-contact is needed at starting, before the arm has left the 'off' stud and become energized. The usual low-voltage retaining magnet is fitted.

¶ Multiple-switch Starters.—For the operation of large motors taking very heavy currents that are beyond the capacity of face-plate contacts or drum-controller fingers, a series of knife switches may be used instead of the latter, forming a multiple-switch starter or controller. The units are then arranged in a row, as in Fig. 31, and employed to short-circuit successive steps of resistance.

Now it would be dangerous for the operator to begin at the wrong end of the line, or even to take any of the switches out of its

proper order. To render this impossible an interlocking bar is arranged to slide horizontally behind all the switches, in such a way that in the 'off' position it absolutely prevents any but the first from closing. When this one is forced home, however, it presses against an inclined edge at the end of the bar, moving it along by, say, $\frac{3}{8}$ in. A gap in the bar, also with an inclined edge, is thus brought opposite the second switch, enabling it to be pushed in. As with the first unit, this opera-



*General Electric Co., Ltd.*

*Fig.* 31. Multiple-switch starter.

tion moves the bar laterally, and the third can be closed, and so on. The last switch, which has to carry the current continuously, is made of more ample proportions than the others. To stop the motor a circuit-breaker is tripped, and this is so interlocked with the starting switches that it cannot be closed again until all the latter are opened.

# V

# RESISTANCE CONTROL

RESISTANCE is employed in the control of an electric motor for tv main purposes, namely, for starting it from standstill to its norm running condition, and for bringing about variations in its workii speed. Both functions are commonly fulfilled by the same type apparatus, which differs mainly in that the one form is designed carry the current only during the starting period, while the other mu be capable of remaining in circuit continuously.

¶ STARTERS.—Every type of motor offers less opposition to the passa of current through its main circuit when it is at rest than when motion; for at standstill it merely constitutes a resistance or impedanc and is not able to develop the counter E.M.F. that restricts the flow current after rotation has begun. Hence the voltage that can safe be applied to its terminals is much less in the former case than wh full speed has been reached.

The simplest method of providing a reduced E.M.F. during t starting period is to interpose a resistance in series with the appropria circuit of the motor (e. g. the armature of a D.C. machine), and th absorb a portion of the applied voltage. Since the energy so abstract is converted into heat, the method is a wasteful one; but it has t great merit of simplicity, which renders it cheap and reliable.

¶ DIRECT-CURRENT STARTERS.—The principle of resistance starting most clearly exemplified in connexion with the D.C. motor, for whi the need of a reduced voltage is the greatest. It is an easy matter realize the heavy current flowing when the armature is stationary, as i ohmic resistance forms the only opposition, and the result is a simp example of Ohm's Law. This resistance is nevertheless sufficient keep the starting current within safe limits for small machines, such shunt motors up to about $\frac{1}{2}$ H.P. and series motors up to about 8 H.P. all of which may be simply switched across the line. A more usu case will however be considered, in order to afford a concrete illustratio of the functions of the starting resistance, and the method in which fulfils its object. For this purpose a motor of average size will be take namely 10 H.P., designed for 440 volts and therefore having a norm full-load current of 20 amperes and an armature resistance [1] of 2 ohm It will be supposed that the field is fully excited at the outset and ke at constant strength, and that the motor is coupled to a mechanic load of constant torque, which imposes normal full load when th motor is up to speed.

If the armature were simply switched on to the line, a current woul flow equal to 440/2, or 220 amperes. This is equivalent to eleven time

[1] For table of Armature Resistances see Appendix, Table 26.

normal full-load current, and would seriously overstress the machine both mechanically, through the shock that would be caused to the shaft, keyway, and coupled load, and electrically, through the overheating of the conductors and brush gear. There would also be magnetic effects in the form of attractions and repulsions between the conductors carrying this heavy current, which might lead to damage if the motor were a large one.

In order to keep the starting current at its normal value a total of 22 ohms would be needed, requiring an added resistance of 20 ohms. It is not necessary, however, to restrict the current peaks to the normal value, and quicker acceleration may be brought about by permitting these to be momentarily of higher values than normal, such as 1·5 times or twice the full-load current. It will be assumed that the current is permitted to rise up to twice normal, but not to exceed it. In this case the total resistance in the circuit at starting would be 11 ohms, the added resistance external to the armature being 9 ohms.

Now it is not found practicable to employ a starting resistance that is cut out in one step except for two classes of motor, which are as follows: (*a*) small shunt motors not exceeding about 4 H.P., in which the armature resistance is sufficiently high to reduce the second current peak to a comparatively safe value; and (*b*) compound or series motors up to about 120 H.P. with automatic acceleration, in which the starting current is reduced by the electrical and magnetic action of the additional field, and the resistance cut out automatically at exactly the right point.

The ideal state of things would be for the resistance to be cut out smoothly and gradually and not in a series of steps. The result of this would be that the current curve would be a smooth line and would not be peaked. Such results are actually afforded by the liquid rheostat, and would be given by the metallic starting resistance if it could be arranged in one length and a sliding contact moved continuously over it. Since this cannot be accomplished, the rule is to reduce the fluctuations of the current to within practicable limits by splitting up the total resistance into a sufficient number of sections and locating successive contacts at these points.

It will assist in tracing the effect of cutting out the resistance in this manner if certain numerical relationships with regard to the performance of the motor are borne in mind. In the first place, the torque is proportional to the product of the field strength and the armature current, irrespective of speed. As however the torque and the field are assumed constant, it follows that when steady conditions have been reached, that is when the acceleration at each stage is completed, a constant value of the current will be reached on every occasion. The counter E.M.F. generated by the motor, however, is proportional to the speed, and the current at any speed can be estimated from the formula:

$$I = \frac{E-e}{R},$$

where $R$ = the total resistance in circuit
and $e$ = the counter (or back) E.M.F.

Returning to the 10 H.P. case, when the current has fallen to a stea value consequent upon the switching in of the motor having an extern resistance of 9 ohms in series with the 2 ohms of the armature, the curre will have fallen to the normal value, i.e. 20 amperes. The volta dissipated in the resistance is therefore $11 \times 20 = 220$ volts, and t remainder, viz. 220 volts, is the back E.M.F. generated by the moto

If the whole resistance were now cut out, there would only rema the 2 ohms of the armature, and the current peak would be that due the sudden application of the voltage of 220 that had been absorbed l the starting resistance, namely 220/2, or 110 amperes. This is aga too high a current, being considerably greater than the 40 amper permissible, and it is evident that only a part of the resistance can l cut out at this stage. In order to obtain a current peak of 40 ampere the total resistance that must be left in circuit is given by 220/40, 5·5 ohms, which would be made up of 2 ohms of the armature an 3·5 ohms external resistance, the remainder, namely 5·5 ohms, beir switched out. The previous performance would then supervene, th motor accelerating until the current reached the normal value, giving voltage drop in the remaining resistance of $20 \times 5{\cdot}5$ or 110 volts. Th back E.M.F. is now 330.

Again, if all the remaining resistance were cut out, a peak current c 110/2, or 55 amperes, would be produced. For a peak of the stipulate 40 amperes, the resistance to be left in circuit would be 110/40, o 2·75 ohms, consisting of 0·75 ohm in addition to the resistance of th armature, and 2·75 ohms would be cut out of circuit. When the curren has fallen once more to 20 amperes, the voltage drop in the resistanc would be 55 volts, and the back E.M.F. would be 385 volts.

If now the remaining external resistance were cut out, the peal current would be only 55/2, or 27·5 amperes. This is well under twic normal current, and the acceleration can be completed in this way.

Thus the motor has been started according to the given condition by cutting out three successive steps of resistance, the total values a each point being 11, 5·5, and 2·75 ohms respectively. The actua values of the resistance sections that are removed may be obtained by subtraction from the above, counting the armature resistance of 2 ohms as the final stage, the series then being 5·5, 2·75, and 0·75 ohms.

The above values are instructive, several points of interest being deducible from them. First, it will be observed that the last stage gives a smaller peak than the preceding ones; and the process would be more efficient if the steps were so graded that all the peaks were equal. Secondly, the total resistances in circuit at the various stages form a regular series, in which any one turn is equal to the previous turn divided by 2, the number representing the peak factor. That is, the resistances form a geometrical progression, the common ratio being that between the peak current and the normal current. Thirdly, the individual resistance sections also form a geometrical progression until the last is reached, when a smaller peak occurred. If the last section had been equal to the resistance of the armature, then the total resistance

in circuit would again have been halved when the last switching operation was carried out, and the peak would again have been equal to twice normal. The resistances could thus have been graded in such a way as to give equal peaks, all of a somewhat smaller value than that adopted, and the sections as well as the steps of total resistance would have been in geometrical progression.

It is thus seen that the simplest method of calculating such a series of resistances would have been to start with the resistance of the armature and work backwards, multiplying at each stage by the peak factor. It will be instructive to carry this out in the present case, first of all by trial and error. A value of the peak factor of 1·82 may be arrived at in this manner, which would give total resistances, starting with that of the armature of 2, 3·64, 6·62, and 12·07. From these figures the initial current will be seen to be $\frac{440}{12 \cdot 07} = 36 \cdot 4$ amperes; and the peak current at each stage is given by $20 \times 1 \cdot 82 = 36 \cdot 4$ amperes. Thus the initial current and each succeeding peak all have the same value.

Instead of finding this ratio by trial and error, it may be rapidly found from the simple formula:

$$r^{n+1} = \frac{E}{aI},$$

where $r$ = peak factor,
$n$ = number of sections of resistance,
$E$ and $I$ = normal volts and amperes of the motor,
$a$ = armature resistance.

In the present case the formula becomes:

$$r^4 = \frac{440}{2 \times 20},$$

i.e. $$r = \sqrt[4]{11} = 1 \cdot 82.$$

Such a relationship can be easily calculated by means of a slide rule or logarithms.

The individual sections of resistance are given from the previous figures as 1·64, 2·98, and 5·45, these being of course in the reverse order. It would be interesting for the reader to calculate the peak currents that would have been obtained if the same total resistance had been employed, but had been cut out in equal steps, as was formerly the practice. Such a design would be found to give peaks that are far from equal, the first one being very low and the last very high. It will therefore be realized that a great gain in efficiency has accrued through this way of dividing up the resistance.

In the above treatment of the acceleration of the motor two considerations have not been taken into account. First, the self-induction of the armature has been neglected; and since its effect is to delay the rise and fall of the current, the current peaks would not reach the full values that have been obtained by calculation. It has been found, as

a result of experience with a large range of motors, that actual values of the peaks occurring in practice are very nearly two-thirds of those calculated. Secondly, it has been assumed that a resistance section is not cut out until the motor speed has become steady. In practice this would consume an unduly long time, and it is necessary to proceed with the next step before the current has quite fallen to normal value. No great inaccuracy will be introduced if these two factors are assumed to cancel each other.

The diagram given in Fig. 32 illustrates graphically the rise and fall of the current, the latter being plotted vertically and the time horizontally. It will be seen that the actual time spent upon each step of the acceleration is far from being constant, the latter stages being much shorter than the earlier ones. As a matter of fact, the correct duration

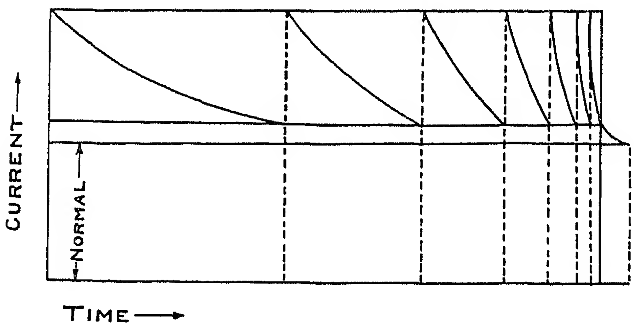



*Fig.* 32. Starting peaks of shunt motor plotted against time.

in each case is proportional to the magnitude of the resistance then in circuit.

It has hitherto been assumed that the load on the motor is such that the torque is maintained constant at all speeds. Such a load would be given by a three-throw pump or a rope brake ; but it should be remembered that there are other types of load met with in practice against which the motor would have to be started. These may be classified as follows :

1. No load, torque practically zero.
2. Fan duty, torque varies as the square of the speed.
3. Self-excited dynamo duty, torque varies as the speed.
4. Brake duty, torque constant.
5. Fly-wheel load, torque maximum at starting.

Since starting conditions are the easier the less the torque at low speeds, the above loads will be seen to be arranged in order of severity, the case that has just been discussed being the fourth, or worst but one. In the two types preceding this, the current peaks, instead of being in a horizontal line, would be in a concave line and a straight line respectively, rising from zero at starting to a maximum at full speed. For

the fifth type of load the peaks would be of a maximum height at starting and would fall as the load rose. It should be realized that it may be a much more onerous task to start a motor provided with a heavy fly-wheel but otherwise unloaded than one which is connected to a load giving full normal current at normal speed.

It is therefore evident that the one set of starting resistances will not be entirely suitable for all types of load even when the same motor is being dealt with. The principal difference between the requirements is that the pauses necessary for acceleration upon the successive steps will vary widely for the different sets of conditions, and for a starter to be exactly suited to the load the heat capacity of the wire used would need to be considerably greater in some cases than others. It is actually the practice of certain makers of this type of apparatus to furnish a special starter for every order. Their stocks of components are so organized that, upon receipt of details of the conditions under which the apparatus is to work, the necessary parts can be quickly obtained and assembled, and the complete product dispatched in almost as short a time as would be taken to supply one ready made. In general, however, it is considered sufficient to make two grades of starter, viz. one for 'ordinary' and the other for 'heavy' duty, and they are divided into these two groups by the British Engineering Standards Association (see B.S.S. 123). Referring to the types of load that have just been enumerated, it will be observed that, apart from the last class (that possessing considerable inertia), a type that is not very frequently met with, the example which has been worked out (that with the constant torque at all stages) is the most severe. The author therefore considers it sufficient to design ordinary starters to fulfil this condition, and to supply a special starter with more robust resistances when heavy duty is specified.

The method of design that has been described for the 10 H.P. motor, resulting in a three-step starter, would be completely satisfactory for a contactor installation, which possesses several advantages over the ordinary manual operation. First of all, owing to the automatic closing of the contacts for each step, the cutting out of each portion of the resistance can be relied upon to take place at exactly the right time. Secondly, a positive and robust contact is made, by means of separate magnet-operated switches, ensuring that the minimum of heating and arcing occurs. No further modifications in the calculated design are therefore necessary in this case.

But for hand operation the case is rather different. First, there is no guarantee that the starter arm will be moved over the contacts at anything like the calculated speed, and thus the current peaks will be of an irregular nature. It will be remembered that for the utmost accuracy the handle speed should increase regularly as acceleration proceeds; and although an operator who is watching the motor would instinctively do this to a greater or less extent, it is unlikely that he would achieve anything like the results demanded by theory. Secondly, owing to the nature of the sliding contact used with face-plate apparatus,

electrical conditions are far less satisfactory than with contactors. At best, the moving contact slides on to the fixed stud gradually, and if a current exceeding about 50 amperes has to be switched on in one step, overheating occurs, especially along the forward edges, and spluttering and arcing takes place. In addition, arcing is apt to occur between two adjacent contacts if the current is *broken* between them when the arc voltage, measured by the product of the current passing and the resistance of the step, exceeds about 50. It was the custom at one time, when lower voltages were the rule, to increase the number of studs until the difference of potential at two adjacent contacts did not exceed 35 volts. This is impossible now, but the effort is always made to keep the maximum voltage down as much as possible. The matter is of the less importance in that there is no need to *break* contact at all in normal starting; burning on this account being therefore due to careless or nervous handling or to emergency conditions. Finally, it is often necessary to employ stock resistance units for these necessarily cheap articles, and it is hence not always practicable to employ the exact values of resistance that have been found correct by calculation.

The custom therefore is to use a great many more steps than are theoretically required. If the current to be made upon the first stud exceeds 40 or 50 amperes, an introductory stud or studs would be used in order to increase the current gradually in steps of not more than this value at the most. When fully loaded, the motor does not start on these preparatory steps and is not expected to do so. They are, however, very useful when a start at no-load is desired, as they enable this to be effected smoothly. Over the rest of the acceleration a reduced peak factor is employed in the design, in order to give a larger number of studs for this portion of the resistance also.

An actual example of a starter designed for 10 H.P. at 440 volts is appended which will serve to show the difference between theoretical and practical conditions. This has a total of 10 live studs, the moving contact resting upon an insulating stud of asbestos composition when in the 'off' position. The following table gives the current at each step, the total ohms in circuit, the resistance of each section, and the gauge of wire of which each section is wound. The latter is added as a matter of interest at this stage, to indicate the increase that is necessary in the size as the time increases during which each section is in circuit.

The table shows that although the peak current does not reach 30 amperes, there are actually three preparatory steps employed in leading up to this; and seven steps are then devoted to the actual acceleration of the motor. The manufacturing practice in this particular case was to give each section the exact calculated resistance (the peak factor being 1·41); the lengths of nickel-copper wire required being specified by the designers and wound on the bobbins in correct succession.

In starter calculations involving the resistance of the armature, it is important that the figure employed should include the resistance of any additional windings connected permanently in series with it, such as commutating and series field coils. The first of these adds about one-

third to the armature resistance; while the second varies in effect according to whether it is merely an auxiliary compound winding, or the main field of a series machine. In the latter case the percentage to be added would be about 40 per cent. and in the former about 10 per cent. It should be understood, however, that these figures are very approximate, and whenever the exact values are obtainable for a particular design they should be asked for and employed. Many designers also add an allowance for the resistance of the armature leads, a usual figure being four-fifths that of the armature itself.

TABLE 4. DETAILS OF RESISTORS AND CURRENTS FOR EACH STEP DURING STARTING OF 10 H.P. 440-VOLT SHUNT MOTOR

| *No. of Stud.* | *Current Amperes.* | *Ohms in Circuit.* | *Ohms in Sections.* | *Gauge of Wire S.W.G.* |
|---|---|---|---|---|
| 1 | 10 | 42 | — | — |
| 2 | 15·7 | 26 | 16 | 21 |
| 3 | 22 | 18 | 8 | 21 |
| 4 | 28·2 | 13·5 | 4·5 | 21 |
| 5 | 28·2 | 9 | 4·5 | 20 |
| 6 | 28·2 | 6 | 3 | 19 |
| 7 | 28·2 | 3·5 | 2·5 | 18 |
| 8 | 28·2 | 2 | 1·5 | 18 |
| 9 | 28·2 | 0·8 | 1·2 | 17 |
| 10 | 28·2 | 0 | 0·8 | 16 |

The starting of series and compound motors is somewhat less onerous than with the shunt type, and although the standard starter is generally expected to serve for all types of motor, in cases where the equipment is large enough to justify special attention being given to the resistances a somewhat smaller and therefore cheaper set of these might be prescribed. The full series motor will first be briefly considered.

The fundamental change introduced by the series field consists of the rise and fall of the excitation with the armature current. In consequence, the field strength also increases immediately a section of resistance is cut out, and brings about a corresponding increase in the back E.M.F. The method of calculation given on p. 55 for the shunt motor will therefore require modification at the beginning of every step by the appropriate increase of $e$. Since however the flux does not rise proportionally to the excitation owing to the approaching saturation of the iron at normal densities, it will be necessary to obtain this flux factor from a curve representing the increase with load for the machine under consideration. A representative set of such curves is given in Fig. 33, from which it is seen that for a series motor the flux and therefore the back E.M.F. rise by 25 per cent. for a twice normal peak. For a 15 per cent. compound motor the increase will only be about 7 per cent.

In addition to this change, it must be remembered that both the resistance and the self-induction of the armature circuit are considerably increased by the addition of the series coils. Not only will the resistance finally left in circuit be increased to the extent of about 40 per cent. by

the former, but the rate of growth of the peak current is much retard
by the latter. The average torque is also rendered greater by t
series turns, and the duration of the starting period is shorter. Th
a smaller value of resistance is needed, and it may be made of smal
section. By bearing these modifications in mind, and also rememb
ing that the resistance steps will still be in geometrical progression, t
designer will have little difficulty in applying the calculation alrea
given to the cases of the series and compound motors.

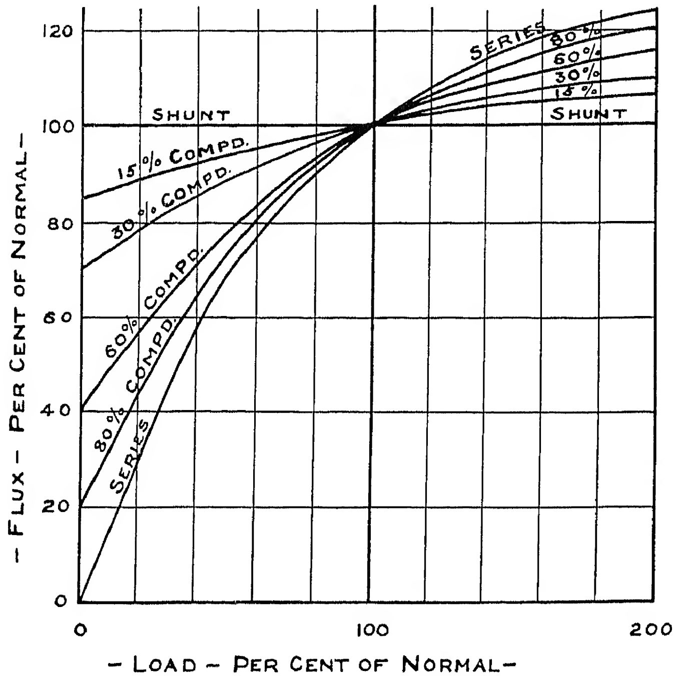



*Fig.* 33. Approximate flux curves for various D.C. motors at varying load.

It has been found by the author, as a result of comparative tests b
means of the oscillograph upon shunt and series motors of identic
design and horse-power, that when the same resistance steps are em
ployed for both, the first peak is reduced by nearly 20 per cent. whe
changing from the shunt to the series type, as would be expected fro
the statical effect of the series field ; but succeeding peaks are reduce
to less than half their height above the normal value. If an exa
calculation were not required, therefore, the simple shunt formula migh
be employed, and these allowances made in applying it.

There are a few details in connexion with the electrical and mechan
cal design of D.C. starters which require noting. In the first plac

whenever the shunt field of a motor has to be switched in or out, it is essential that the circuit should not be suddenly broken, owing to the high self-induction of such a winding. The usual expedient is to provide a discharge path whereby the ' inductive kick ' may be dissipated, which sometimes takes the form of a shunt circuit containing a resistance comparable with that of the field itself. In the case of an ordinary starter a simpler method is possible, consisting of the connexion of the armature, field, and starting resistance in a ring circuit which is never

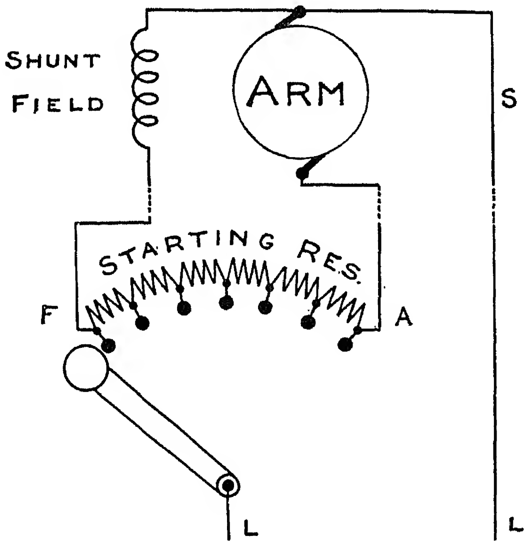



*Fig.* 34. Diagram of connexions for ordinary face-plate starter, shown connected to a shunt motor. *Note.*—A series field, if present, would be inserted at *S* ; while for a series motor the shunt field would be omitted.

broken, the resistance being simply cut out of the armature circuit and into the field, as shown in Fig. 34. When the motor is stopped, then, the persistent current in the field is able to dissipate itself without giving rise to a dangerous potential, which would otherwise break down the insulation, in the course of time, at some point in the field circuit, such as, for example, at the brush support. The magnitude of the starting resistance, as compared with that of the field, is too small to affect the excitation appreciably when cut into circuit with it.

Since it is dangerous to leave a motor connected to the line with the starting resistance cut out, and since this would happen if preventive steps were not taken whenever the voltage failed and was switched on again, it is necessary to provide an automatic device whereby the starter arm is moved to the ' off ' position when the voltage is removed. This is accomplished by the well-known low-voltage (or ' no-volt ')

release, consisting in the case of D.C. motors of a small electro-magne energized by a winding that is generally connected for convenience ir series with the shunt field of the motor. By this arrangement th no-volt coil can be composed of a comparatively few turns of thick wir designed to carry the field current. For series motors, which have no this convenient field, it is necessary to wind a high-resistance coil o fine wire and connect it in series with a suitable resistance unit acros the line. One or two firms employ this method for all their starters so that one type only is required for both shunt and series motors but the simplification and additional reliability introduced by the pre vious arrangement makes the latter well worth adopting when it i applicable. A further advantage is that the starter arm flies back i the shunt excitation fails, preventing the motor from flashing over.

It is convenient to fit a further device which causes the starter t open the circuit upon the occurrence of an overload. This takes th form of a simple auxiliary switch short-circuiting the contacts of th no-volt coil and thus causing the arm to travel back. A switch of thi type has already been illustrated in combination with another devic in Fig. 28. The auxiliary contacts themselves are closed by a sma series-wound electro-magnet that lifts the armature to which th contacts are attached when the current passing through the coil is c sufficient strength. Adjustment of the tripping current is effected b variation of the height of the armature relatively to the magnet pole It should be noted that by interrupting the circuit in this way the mai current is broken at the starter studs, and if it were not for the hig speed at which this rupture of the current normally takes place, burr ing would occur at the studs. Apart from this, the rule is made th the motor circuit must always be broken at the switch provided wit the equipment. In spite of this care, a certain amount of burnin at the contacts may occur, and for starters of the larger capaciti (i. e. above about 25 H.P.) they are designed to be renewed fro the front.

¶ Starters for Wound-rotor Induction Motors.—The princip of the induction motor is similar to that of the D.C. pattern, but in th case the field flux rotates and cuts the windings of the rotor. F starting purposes, a resistance is included in the circuit in series wit the rotor, when of the 'wound' pattern, and this is cut out as befor The design and grading of the steps is in general similar to D.C. pra tice, the various sections being in geometric progression. The cas differ, however, in that there are now three phases in the resistan as well as in the rotor and it is necessary to cut out steps in a of them.

There are two methods of short-circuiting this resistance. Firs the connexion may be made across all three phases so as to cut out section in each. This would be exemplified in Fig. 35 by making contact right across the three resistances at $A$, whereby sections $R_1$ $R_2$, and $R_3$ would all be short-circuited. The second alternative

to cut out the individual resistances in turn. For example, six steps of acceleration could be obtained in the diagram by short-circuiting first $R_1$, then $R_2$, and so on up to $R_6$, when full speed would be attained.

In the latter case, all the six resistances would be in geometric progression. Their magnitude can be estimated owing to the fact that when, say, $R_1$, $R_2$, and $R_3$ are graded in this manner, their effect on the running of the motor is exactly as though they were identical and all equal to $R_2$. Although there is a certain amount of unbalancing during the starting stages owing to there being somewhat more resistance in one phase than another, this inequality will be kept uniform throughout the acceleration if they are in geometrical progression, and the whole operation of starting can be made smooth by ensuring that the last resistance $R_6$ is of the right value relatively to that of the rotor. To do this it is only necessary to imagine that the three windings of the rotor are also in geometrical progression, continuing the series already begun by the resistances, and then to represent the resistance of the rotor by the middle term of these three. In this way the resistances can be designed and graded without difficulty. Reference to Fig. 35 will make the matter clear.

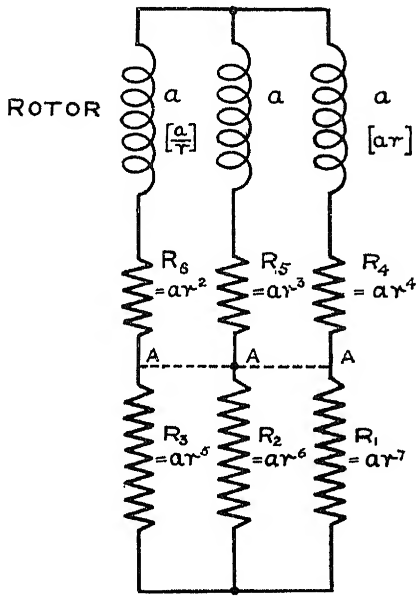



*Fig.* 35. Resistance starting of wound-rotor (or 'slip-ring]') induction motor.

The particulars required for designing the starting resistance are the rotor resistance, the rotor voltage, and the starting torque to be developed, the last being usually specified by giving the current to be passed on the first stud. As a similar stipulation is frequently made in connexion with D.C. motors, and the total resistance thus obtained must be so graded as to give equal peaks, the present case will serve as an example for both types of motor.

The illustration shows the three equal windings of the rotor, each with a resistance represented by $a$ ohms, at the top of the diagram. To obtain the last step of resistance, substitute $\frac{a}{r}$, $a$, and $ar$ for the phases of the rotor, whence it is seen that the next term in the sequence is $ar^2$, and so on as marked in the figure.

If $E$ is the rotor phase voltage, and $I$ is the rotor current on the first stud per phase, and $R$ is the total resistance in circuit at starting per phase, then

$$R = \frac{E}{I}, \text{ very nearly.}$$

The above simple relationship holds for all practical purposes, as the reactance of the winding is negligible under starting conditions. For when the rotor is stationary, all the external resistance is in circuit; and as the reactance is in quadrature with this, it makes very little difference to the resultant. As the resistance is cut out, the speed rises and the slip decreases, so that the frequency of the rotor current is reduced and with it the reactance. At full speed, the latter is only about 1 per cent. of the standstill value.

An illustration from actual practice may be quoted. In a typical example of a slip-ring motor, the rotor resistance per phase ($a$) = 0·072 ohm, and the total reactance per phase = 0·85 ohm, made up of stator reactance — 0·55 ohm, and rotor reactance — 0·30 ohm. The total resistance at starting is determined below to be 13·1 ohms, or an average of 4·4 ohms per phase, which is large in proportion to 0·3 ohm; while the resistance and reactance at full speed are respectively 0·072 and 0·006 ohm.

The rotor is to pass full-load current on the first stud.

$$\text{Then } ar^6 = \frac{E}{I} = 6{\cdot}25.$$

$$\text{But} \quad a = 0{\cdot}072;$$

$$\therefore \quad r^6 = 86{\cdot}9$$

$$\text{and} \quad r = 2{\cdot}1.$$

The grading is then as shown in the following table:

TABLE 5. VALUES OF RESISTANCE DURING STARTING OF SLIP-RING MOTOR

| *No. of Step.* | *Total Resistance in Circuit. Ohms.* | *Resistance of each Section. Ohms.* |
|---|---|---|
| 1 | 13·1 | 6·85 |
| 2 | 6·25 | 3·25 |
| 3 | 3 | 1·57 |
| 4 | 1·43 | 0·75 |
| 5 | 0·68 | 0·36 |
| 6 | 0·32 | 0·168 |
| Rotor | 0·152 | 0·072 |
| Rotor | 0·072 | 0·072 |
| Rotor | 0·034 | 0·072 |

¶ CONTROLLERS.—When an armature rheostat is intended to maintain the speed of the motor at some partial value for prolonged periods, a number of modifications are required in the design. The chief of these is in connexion with the resistance, the whole of which must be capable of carrying full-load current continuously. It will thus be much more bulky than in the case of a starter.

Further, a controller (or series regulator, as this type is often called) is called upon to cut steps of resistance in as well as out, and the contacts must therefore be adapted for frequently breaking circuit, in contradistinction to those of a starter. A drum type of controller, with the normal number of steps, will fulfil this condition. For the face-plate type, specially robust contacts, with auxiliary arcing studs, will meet the case, but will not be suitable for such frequent operation as the drum. An alternative is to provide a larger number of steps, so that the voltage ruptured on any stud is kept down to a constant small

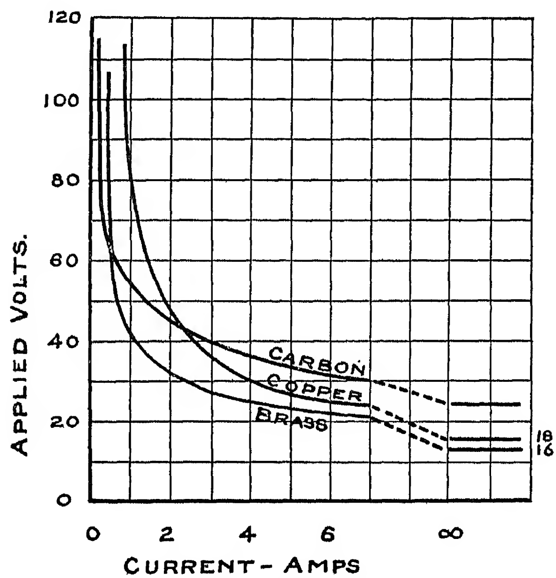



*Fig.* 36. Curves giving maximum current broken without arcing at various voltages between contacts of three materials.

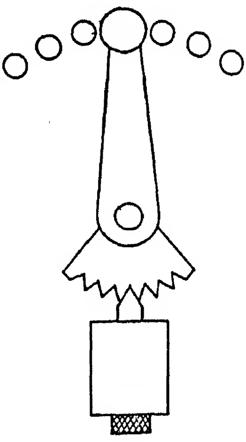
figure. In this connexion the curve shown in Fig. 36, due to Krauss, is of interest, showing the values of the voltage and current below which no burning can occur. For example, any current may be ruptured at 16 volts without fear of arcing. These figures, however, must in the majority of cases be regarded as an unattainable ideal, and the effort is made to keep as close to them as possible.

The reasons for the use of a low-voltage release hold good for controllers as for starters. Its design is now a little more difficult, since it must be able to operate at any position of the arm. The usual modification is shown in Fig. 37. A spring-off arm may be obviated, however, by substituting a low-volt interlock, which instead of restoring the arm to the off position prevents the circuit from being remade until the arm has been returned by hand. This may take the form of an electro-

magnet which is able to hold closed a gap in the main circuit, but is not strong enough to reclose it. The device is so located that reclosing is brought about mechanically by the arm itself as it reaches the 'off' stop. An example of this form of low-voltage protection may be seen in Fig. 197.

¶ FIELD REGULATORS.—The increase of motor speed by means of a field (or 'shunt') regulator does not call for any elaborate mathematics. The total resistance is fixed by the specified speed ratio; and grading is employed to give a constant increment of speed at every step.

To raise the normal speed by a given factor, the field flux must be weakened by that factor in order that the rate of cutting lines of force may be kept constant. Now the standard motor field is designed at about the knee of the magnetization curve, and the field strength is thus not even approximately proportional to the ampere-turns of the coils. This curve should if possible be obtained for the motor in question, and the resistance designed to weaken the excitation appropriately.



No-volt coil (acting against spring).

*Fig.* 37. Arrangement of low-voltage release for series regulators or controllers.

Such a 'saturation' curve for an average commercial motor is given in Fig. 38. This diagram, which is really the *B–H* curve for the magnetic circuit of the motor, is obtained by varying the excitation and measuring the voltages on open circuit. There is no need to consider also the full-load saturation curve as with generator rheostats, as the effects of the load, namely, *IR* loss and armature reaction, oppose one another and produce little effect on the speed. Let it be supposed for the sake of example that the latter has to be doubled; then the voltage at normal speed has to be halved, and the curve shows that the excitation must be decreased in the ratio 1 : 0·36. A resistance must therefore be inserted in series with the field having a resistance $\frac{1-0{\cdot}36}{0{\cdot}36}$ that of the field, or 1·8 $R_F$. The same method serves for any speed ratio up to the usual maximum of 5 : 1.

If it were desired to weaken the excitation by regular steps, the sections of resistance would be tapered so that each section removed would be a constant fraction of the total resistance left in circuit. That is, if $R_1$ and $R_n$ are the first and last sections of the total regulator resistance $R$, and if $R_F$ is the resistance of the field, then

$$\frac{R_n}{R_F} = \frac{R_1}{R_F+R-R_1}, \quad \text{or} \quad \frac{R_n}{R_1} = \frac{R_F}{R_F+R-R_1} = \frac{R_F}{R_F+R} \text{ (approx.)}.$$

This relationship will enable the grading to be effected fairly correctly, or the common ratio may be calculated as

$$r = \sqrt[n-1]{\frac{R_F}{R_F+R}} \text{ (approx.).}$$

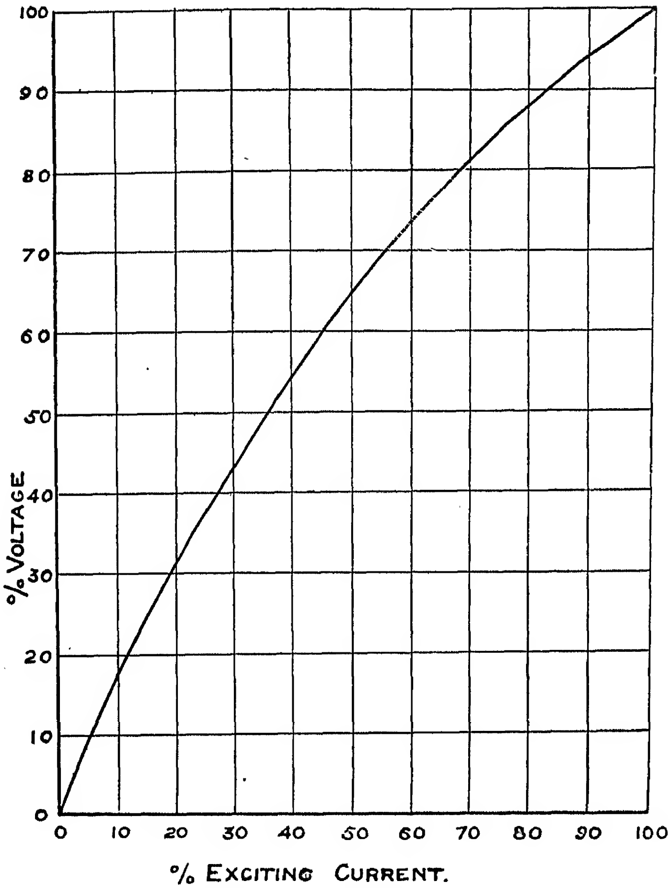
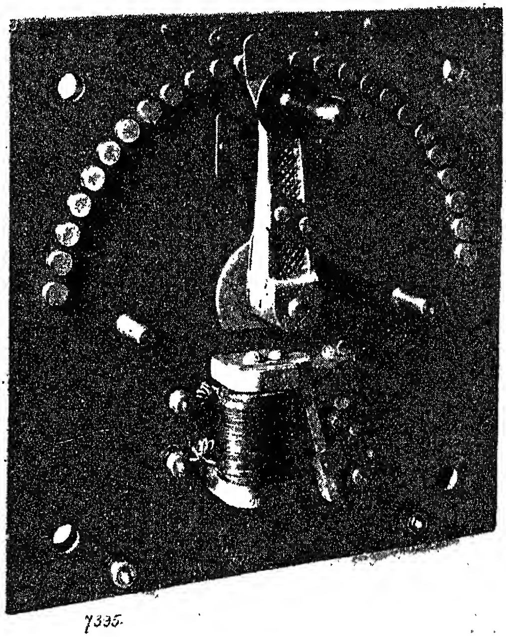



*Fig.* 38. Saturation curve of average shunt motor.

It is not usual to take any great pains to make the steps exact. When the speed ratio is greater than about 2 : 1, at least the major steps of voltage should be scaled off from the saturation curve and the resistance sections proportioned accordingly.

It is most inadvisable that a motor should be switched in with a field regulator in circuit, and some such device as the low-voltage inter-

lock described above, or a field-accelerating relay, should be used. An illustration of a suitable interlock is given in Fig. 39. It is also important that a motor field regulator should not be liable to open the circuit completely, as this would cause failure of the excitation altogether, and a very great increase in the speed. For this reason it is the best practice to connect the free end of the resistance to the same terminal




*General Electric Co., Ltd.*

*Fig.* 39. Interlock for field regulator to prevent motor starting on a weak field; it short-circuits the whole resistance until the small armature is moved against the poles.

as the contact arm, so that the circuit is not entirely broken even if the contacts are separated by dirt or mechanical damage.

Occasionally, as in motor-generator control systems, generator field regulators have to be designed as part of the scheme for governing a motor. In this case it is customary to work from the no-load and also the full-load saturation curves, the latter being approximately parallel to the former. When a resistance is being got out to reduce the voltage from a maximum to a minimum, the full range of adjustment required is obtained by employing the full-load curve at the higher voltage, and the no-load curve at the lower. Average curves are given in Fig. 40.

If it were required to vary the generator voltage down to a very low value, an excessive amount of resistance would be necessary with the

ordinary type of regulator, and a potentiometer pattern is employed. In this the whole resistance is connected across the line, and the moving contact taps off desired fractions of the full voltage at various points along the length. By employing two moving contacts, one at

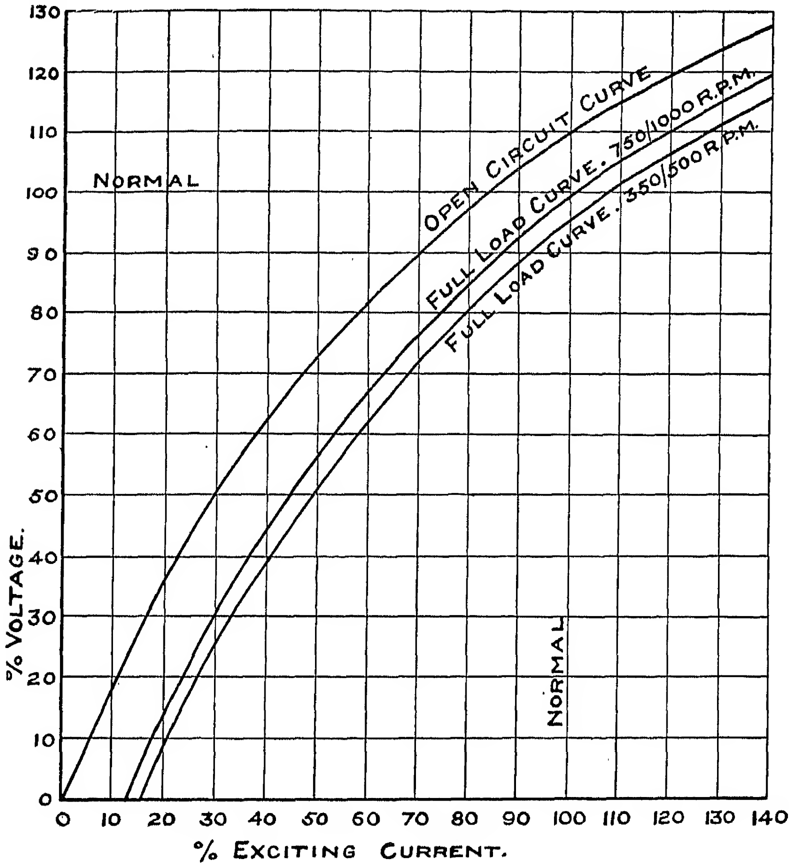



*Fig.* 40. Saturation curves of average shunt generator.

each end, one may be used for coarse adjustment and the other for fine; and a very even and smooth graduation of the voltage may be obtained right down to zero. A potentiometer regulator is illustrated in Figs. 143 and 144.

¶ Eddy Current Controller.—An indirect method of inserting resistance in the rotor circuit, and of reducing it automatically without requiring moving switchgear, is available when partial running speeds

are not desired. The apparatus simply consists of a three-phase inductance connected permanently to the rotor terminals, having a solid iron core in which eddy currents are generated by the usual transformer action. Since the resistance loss due to these depends upon the rotor voltage and frequency, which decrease as the rotor accelerates, the desired result is attained ; except that a small percentage of the loss persists after full speed has been reached.

# VI

## MULTIPLE VOLTAGE AND SERIES-PARALLEL CONTROL

INSTEAD of controlling the speed of a D.C. motor by dissipating part of the voltage supplied to the armature in the form of heat, as is done in a resistance controller, a similar end could be attained without the same waste of power by the direct supply of a fractional voltage for connexion to the armature. In this way a definite lower speed (or

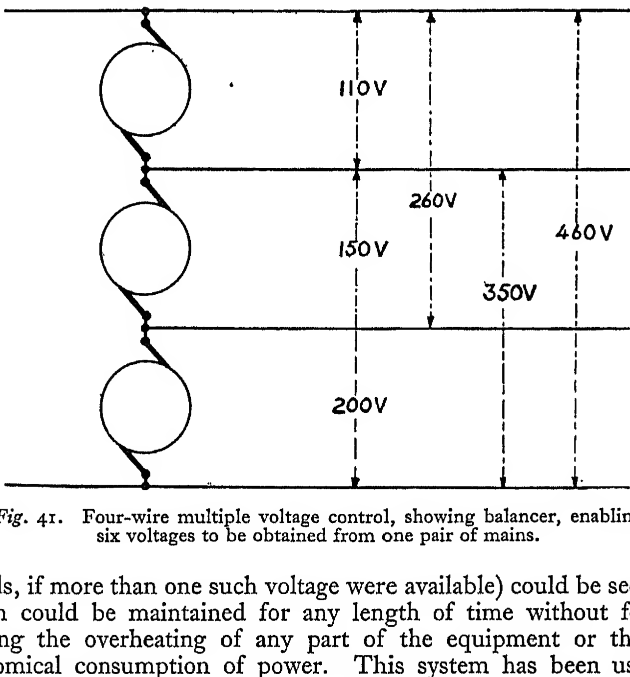



*Fig.* 41. Four-wire multiple voltage control, showing balancer, enabling six voltages to be obtained from one pair of mains.

speeds, if more than one such voltage were available) could be secured, which could be maintained for any length of time without fear of causing the overheating of any part of the equipment or the uneconomical consumption of power. This system has been used to some extent in the past, as many as five wires being employed in the distribution of power through a works in order to provide a choice of four running speeds. The method has, however, proved too complicated and costly and has largely fallen into disuse. It is significant that even the numerous establishments that have three-wire installations rarely avail themselves of the opportunity of obtaining half speed in this manner, but as a rule prefer the standard rheostatic method of control.

The diagram forming Fig. 41 shows a method that has attained some vogue for providing a series of six voltages from the one pair of mains, by the use of two additional leads and a balancer set. By designing the

three machines of the latter to give voltages of 110, 150, and 200, and joining them across the 460-volt mains, a suitably graded progression of 110, 150, 200, 260, 350, and 460 volts is given; while another appropriate series is 60, 80, 110, 140, 190, and 250 volts.

For examples of three-wire control, employed to secure wide speed adjustment, see 'Calenders and Printing Presses', forming Chap. XXII. The multi-wire method has also been revived to some extent for the control of lifts.

A more convenient way of securing half normal voltage, and therefore a proportionately reduced speed, is available when two similar motors are employed to share a common load. This is the well-known series-parallel system of control that is so generally applied to electric traction, whereby the motors are first connected in series and accelerated to half speed; and when full speed is required they are reconnected in parallel with the starting resistance again cut into circuit, and once more accelerated until they are directly connected across the line. The method is used to some extent in industrial control, notably for large cranes and unloading bridges (Chap. XX), and it should be borne in mind when a scheme is being got out which is to include economical running at half speed. It may even be applied to a single motor, if the armature be provided with a duplex winding and two distinct commutators and sets of brush gear. Such a machine is a perfectly practical one, its chief drawback being a lowered capacity through increased difficulty in securing effective armature ventilation.

The main problem involved in series-parallel control is due to the necessity for altering the main armature circuits in order to change the connexions. Smooth acceleration, combined with an uninterrupted torque, is thereby rendered difficult of attainment. There are four practicable schemes whereby the change-over may be effected, these being given in the following list: (1) separate change-over switch; (2) open-circuit transition; (3) short-circuit or shunt transition; (4) bridge transition.

¶ Separate Change-over Switch.—The first and most elementary method differs radically from the others in requiring two pieces of apparatus, namely the usual accelerating switch or drum and a series-parallel change-over switch, preferably interlocked with it. Greater complication is the result, as compared with the single drum methods, and hence this one is only used when half speed is required for considerable periods. In one design of controller the accelerating drum is moved through half a revolution with the motors in series, during which the resistance is all cut out. In the following half revolution the change from series to parallel is made by the second drum, the first having again reached the all-resistance-in position by the time the circuit is remade. Still the handle is rotated in the same direction, and in the next half turn the resistance is once more cut out. Moving the handle in the opposite direction then reverses the series of operations, retarding the motor and passing through the series position to rest.

¶ Open-circuit Transition.—The original method for effecting the change-over by means of a single drum was that whereby the circuit was simply broken between the two motors and remade in such a way as to place them in parallel. This is illustrated in the upper two diagrams of Fig. 42, of which No. 1 shows the motors at the end of the series stage, with the resistance all cut out, and No. 2 indicates the

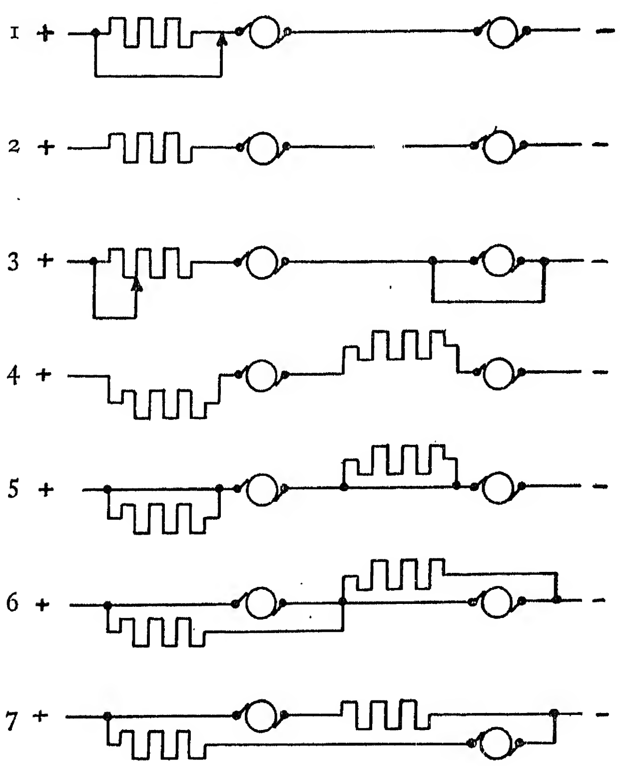



*Fig.* 42. Series-parallel system of controlling two motors, showing the three methods employed in practice.

first step in the open-circuit transition; the two ends of the circuit being subsequently joined up to the remote terminal of the other motor in each case.

This method has the advantage of simplicity, but is inferior to the two following in every other respect. On account of the rupture of the main circuit, heavy arcing is apt to occur which may be difficult to deal with. There is an actual idle period during which all the torque ceases, and it was found, in the case of traction systems with heavy grades, that an ascent at more than half speed was almost precluded by

the difficulty of passing the transition stage. The method is thus only suited for comparatively small motors and for ordinary duty.

¶ Short-circuit Transition.—The method of changing over known as ' short-circuit ' or ' shunting ' transition avoids the interruption of the main circuit by the short-circuiting of one of the motors at the same time as a section of the starting resistance is reintroduced, as shown in Diagram 3 in Fig. 42. While the other motor maintains its torque the inner terminal of the first is disconnected and remade at the outer terminal of its fellow, completing the paralleling process.

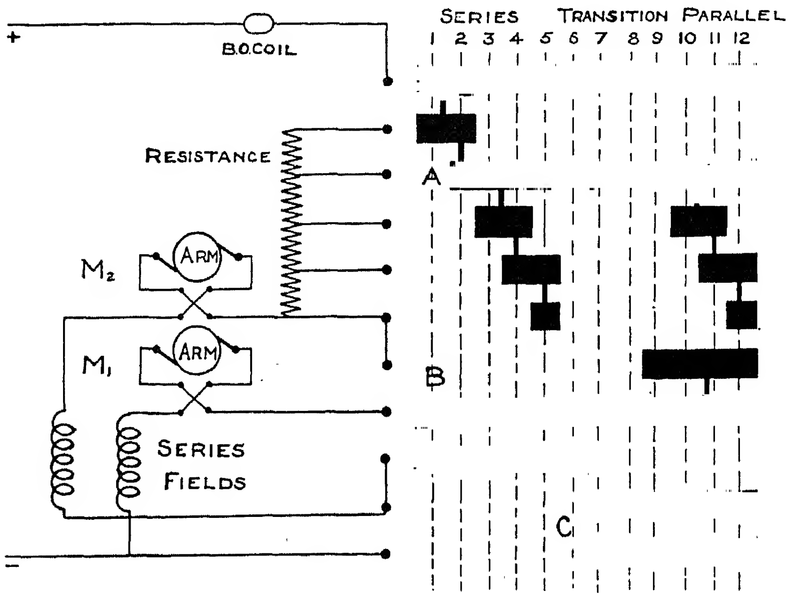



*Fig.* 43. Controller for series-parallel control of two motors, employing short-circuit (shunting) transition.

By virtue of the added resistance the active motor is only subjected to a moderate overload during the transition; while the short-circuited machine, being still in series with the other, sustains no damage during the instant that it is out of action. The effect upon the latter unit is the sudden extinction of the current in the shunted windings, causing the retardation of the armature and a consequent backlash of the gearing that is noticeable when a tram-car is being accelerated. This method is mostly used on ordinary tramway systems, and it is only slightly more complicated than the previous one. Although the driving effort does not cease, the acceleration pauses during the transition period.

An example of this type of series-parallel control is shown in Fig. 43, which includes a reversing drum, indicated by the change-over con-

tacts below each armature. The arrangement should be compared with those for the standard single-motor drum controllers, and the points of difference will be briefly noted. As usual, the numbers at the head of the vertical dotted lines indicate the successive positions in the movement of the controller.

It will first be observed that the third sector from the top, marked *A*, is prolonged instead of having the same length as the second, fourth, and fifth. This is necessary with the short-circuit type of transition, the first stage of which, shown at position 6, is exactly similar to position 2; for the same amount of resistance is cut into circuit again, preparatory to the short-circuiting of the second motor.

The sectors marked *B* are those which connect the field of one motor with the armature of the other and thus place the motors in series. The latter connexion is not removed until after position 7, at which the two sectors marked *C* have come into play, connecting the field of the first motor to the negative line and thus shunting the second motor. From position 8 onwards the sectors to the right of *B* operate, connecting the armature of the second motor to that of the first, and hence reconnecting this motor into circuit in parallel with the other.

¶ BRIDGE METHOD.—The final method, and the one giving the most perfect results, resembles in principle the Wheatstone Bridge. For this arrangement the regulating resistance is connected in two equal halves, one part being between the two motors, as shown in Diagram 4 (Fig. 42). After all has been cut out, as shown in Diagram 5, the resistance connexions are changed to those in Diagram 6, an operation which does not necessarily involve the breaking of any current whatever. It is this diagram that is like that of the Wheatstone Bridge, the connexion in the centre representing the bridge itself, which is shown removed in Diagram 7, constituting the last stage of the transition. The removal of this connexion may be effected without the rupture of any current provided the usual bridge relation holds, namely, that the four differences of potentials involved, being those across the two motors and the two resistors, are equal at the instant following the operation.

The principal impediment to the use of the bridge method for manual controllers is derived from the difficulty on the part of the operator in gauging when the motors are running at such a speed that their back E.M.F. will be equal to the fall of potential down the resistors. For this reason the method is chiefly used for automatic control, where it is easy to secure the change-over at the proper time. In such cases, also, the magnitude of the resistance and the moment of change-over are so adjusted that the resistors pass more current than the motors at the stage shown in Diagram 6 and therefore there is a definite step in the torque between Diagrams 6 and 7. This is possible since contactors are used to break the current, and there is therefore no objection to a difference of potential across the bridge when it is removed. Thus a characteristic of this method is that not only is the torque continuous but also the acceleration.

¶ Further Observations.—The principal advantage of series-parallel control is a saving of much of the power otherwise wasted in the resistance. It will be obvious that this complication will not be justified unless accelerating periods are numerous, and unless half speed is required frequently. It is the prevalence of such conditions that accounts for its use in traction work, where this method is practically universal for D.C. systems, and also for some A.C. examples, in spite of the advantage held out by induction or transformer regulation for the latter cases.

For industrial control the use of commutating poles and stabilizing field windings has increased the practicability of the field control method of varying the running speeds. If it were not for these improvements, series-parallel control would be met with more frequently in stationary work.

# VII

# THE STARTING OF SQUIRREL-CAGE AND SYNCHRONOUS MOTORS

A SQUIRREL-CAGE motor is one in which the rotor winding is completely short-circuited and self-contained, consisting of a cylindrical arrangement of bars joined together electrically by the end-rings, exactly like the article from which its name is derived. No external connexions are brought out from it, and thus its own rudimentary circuit cannot be modified in any way for starting purposes, as is done with the wound rotor and with the armature of a D.C. machine. Any changes that may be effected must therefore be confined to the stator circuit.

The only available modification is thus the temporary reduction of the applied voltage during the starting period. It has already been shown in Chap. III that under starting conditions, that is with the rotor stationary and with the maximum voltage induced in its winding, the power factor of the usual design of motor is too low for a torque to be developed exceeding about one and a quarter times normal. This state of things can be much improved by the insertion of resistance in a 'wound' rotor, since the phase angle is thereby advanced; but such a step is not possible in the present case. A permanently high-resistance rotor has good starting qualities, but is subject to a continuous heating loss when running; and for this reason it is employed for exceptional cases only. For most ordinary industrial purposes the poor torque of the low-resistance squirrel-cage has to be reckoned with.

Practical conditions are perhaps best brought home by means of actual figures. If a motor of this type is switched on to normal voltage, a peak current of five to six times normal occurs, giving the above starting torque. Such a peak is not in general permitted upon a public supply system, and a reduction of the applied voltage is hence called for. The power input, and therefore the torque, are proportional to the square of the voltage, and the original defect is much intensified by this relationship. It can therefore be deduced that the squirrel-cage machine, when started at a reduced voltage, is not adapted for accelerating a load involving more than a moderate fraction of full-load torque, the exact value of which is easily calculable.

Voltage reduction, however, is not always necessary. All supply authorities permit motors up to 2 H.P. to be switched straight on to the mains, and many extend the sanction as far as 5 H.P. But it should be realized that, apart from official regulations, no special starting apparatus is absolutely necessary for any squirrel-cage machine, however large. It is a fact that no damage to the motor will result through direct connexion to the full voltage of the line, from either electrical or

mechanical causes; and except for such unusual cases as the driving of a heavy inertia load through the medium of a lightly proportioned belt, no harm will come to the connected load or coupling device. Unlike the D.C. case, where the starter is primarily needed to safeguard the motor, the squirrel-cage machine is thus equipped solely to minimize the voltage fluctuation due to the sudden current peak experienced upon switching in.

Various methods are available for reducing the voltage applied to the stator. These are as follows: (1) the initial insertion of series resistance; (2) star-and-mesh connexion of the stator windings; (3) transformer reduction. The principles involved in all these methods apply to both polyphase and single-phase working. Special elaboration is required, however, in the latter case, which will be dealt with after the simpler two- and three-phase apparatus have been described.

¶ Simple Switch Starters.—The most elementary form of starter consists of a polyphase knife switch, a set of coupled tumbler switches, or some equivalent arrangement whereby the stator is connected directly to the line. Such a form constitutes a perfectly efficient means of setting the motor to work; but there are two auxiliary attachments that are commonly added to the scheme for protective purposes, the value of which merits consideration.

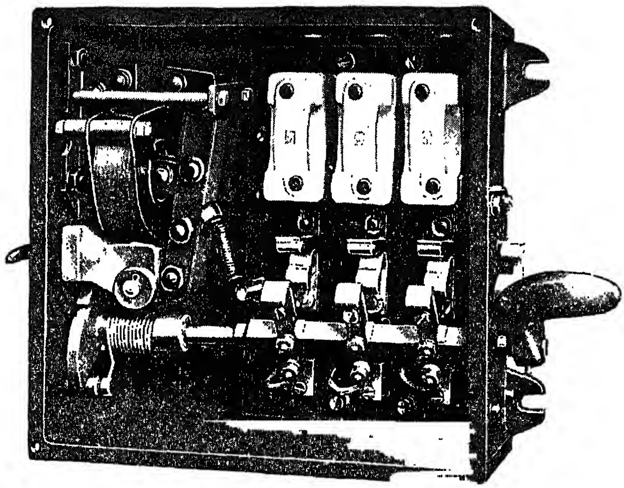
The first of these is a low-voltage release, designed to bring about the opening of the contacts upon failure of the line pressure. There is not the same danger to the windings as exists under similar circumstances with the D.C. machines; but it is still highly advisable that the motor should not be liable to restart without warning upon reconnexion of the voltage. Consequently this accessory is a valuable, and in the opinion of many an indispensable, addition to the starter.

The other elaboration is a provision for preventing the overload cut-outs (fusible or otherwise) from being operated by the starting peak. A common device for this purpose is the addition of special contacts that cut these out of circuit in the starting position. For large motors of, say, 20 H.P., which take a comparatively long time to accelerate, some such expedient is a necessity, and it seems to have been almost generally assumed that it is also necessary for machines of 5 H.P. and less. The author, however, has verified that the duration and magnitude of the peak, even for simple switch starting, are incapable of melting fuses designed for twice normal current under any likely loading conditions. This complication should therefore not be employed unless actual tests have shown it to be required for the starting conditions in question.

A model designed by the author for switch starting is shown in Fig. 44. This is a finger type of switch, provided with no-volt release, and with preliminary contacts for cutting out the fuses. A pause in the starting position is enforced by a simple 'sequence' device, or check pawl, at the starting handle. This model is designed for motors up to 7½ H.P. A compact form of release has been adopted, consisting

of a laminated electro-magnet with a shading ring, the armature of which holds a catch in position against spring pressure, locking the moving contacts in the ' on ' position.

As has been already stated, the switch starter is applicable to all squirrel-cage machines ; and it gives the most rapid and economical starting possible as far as power consumption is concerned. For large motors a duplicate set of fuses may be used in conjunction with the second form, of which the heavier are cut in by the starting, and the lighter by the running contacts. The general rule should be to employ plain switch starting whenever the local regulations will permit.



*General Electric Co., Ltd*

*Fig.* 44. Switch starter with no-volt release for A.C. motors.

¶ Resistance or Rheostatic Starters.—The preliminary insertion of series resistance is a common method of reducing applied voltage in electrical engineering. Unlike the use of rotor resistance, it has no beneficial effect upon the starting torque, which is lowered just as with other stator starters. It is also somewhat wasteful of energy, as a certain proportion of the power that is prevented from appearing in the motor owing to the reduction of voltage is converted into heat, increasing the power demand upon the line ; while the heating of the resistances restricts the number of operations a given model can carry out in a given period. On the other hand, it is cheap and compact, and readily admits of the acceleration being performed in a number of steps. The connexion of a resistance in series with the stator also advances the phase angle of the latter ; and this action not only reduces the magnitude of the current that would otherwise be drawn off, but lessens the interference with the line voltage due to the presence of wattless

current. It would seem at first sight that the defects of the method outweigh the advantages, as this form of starter is not used at all extensively, and is confined to the smaller capacities. Actually, it is superior to the auto-transformer method according to the considerations which have brought about the use of a starter.[1]

The estimation of the appropriate resistance to be used in any particular case is not easy, as both the resistance and the reactance of the

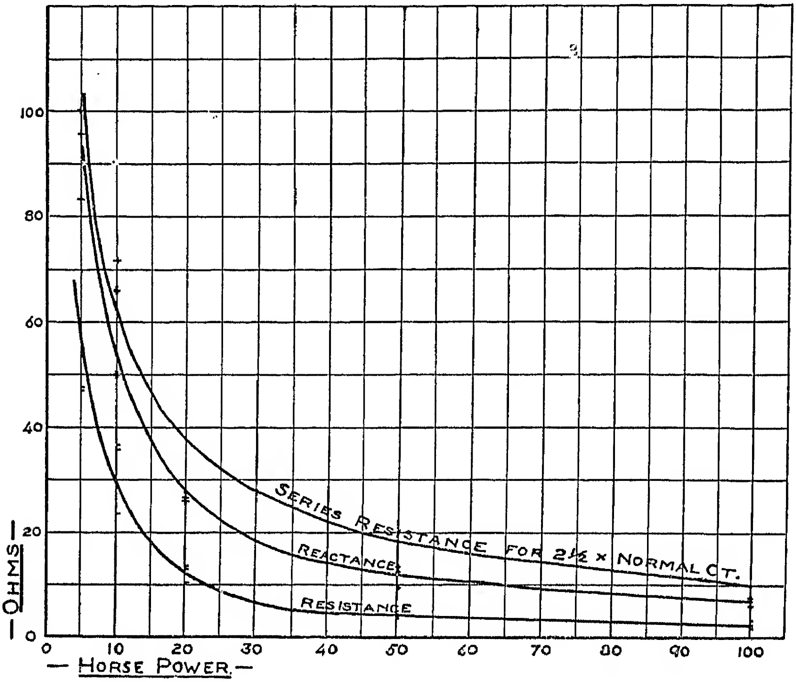



*Fig.* 45. Curves giving average reactance and resistance of squirrel-cage motors at 440 volts and 50 cycles: also the series resistance needed to give two and a half times normal current at start.

stator must be known to enable a desired reduction of the applied voltage and current to be effected with certainty. Fortunately, the need for accuracy is considerably diminished by the use of a series of steps, the number of which is usually in the vicinity of four. The curves in Fig. 45 will assist in making the determination, these giving average values of the stator resistance and reactance for motors up to 100 H.P. at 440 volts and 50 cycles, values for other circuits being simply calculated from these as shown on pp. 139–40; and also giving the average series resistance needed to reduce the starting current peak to two and

[1] See Bailey, 'Starting of Polyphase Squirrel Cage Motors', *Journal A.I.E.E.*, Nov. 1923, p. 1172.

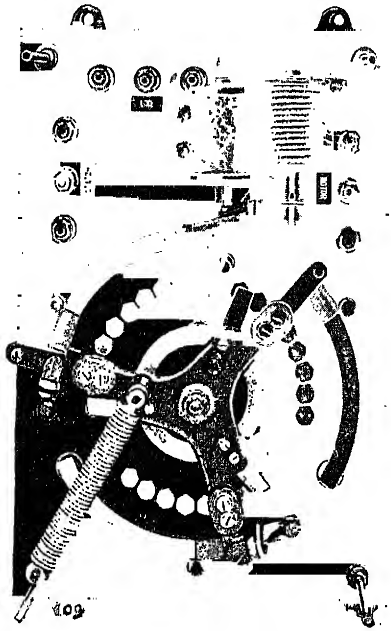
a half times normal. A general formula for arriving at a series resistance which will reduce the starting current to $n$ times its normal full-load value is as follows:

$$r = \sqrt{\frac{E^2}{n^2 I^2} - X^2} - R,$$

where $r$ is the series resistance required, $E$ and $I$ are the rated voltage and current, $X$ and $R$ are the stator reactance and resistance. A similar formula for reducing the voltage across the tator to $n$ times normal is:

$$r = \sqrt{\frac{R^2}{n^2} + \left(\frac{1}{n^2} - 1\right) X^2} - R.$$

When the total resistance has been arrived at, it may be divided into steps in much the same way as has been described for D.C. starters. An example of a rheostatic stator starter possessing both low-volt and overload releases is shown in Fig. 46.



*George Ellison.*

*Fig.* 46. Rheostatic starter for squirrel-cage three-phase motor, showing low-volt and overload releases.

A variant of this method is to use reactance instead of resistance, consisting of coils of insulated wire wound on a laminated frame, exactly as in the case of a transformer. The consumption of power in the starter is now almost done away with; but the power factor is poorer than with the resistance type. This pattern is almost entirely confined to very small capacities, such as those involved in the starting and speed control of fans. There is a tendency for laminated devices to emit an audible hum; and as complete silence is frequently insisted upon for such apparatus, this defect must be countered by an especially rigid construction.

¶ STAR-MESH STARTERS.—The simplest method of reducing the voltage across the stator windings is to bring out both ends of each phase to separate terminals, and to employ a starting switch that connects these first in star and then in mesh. It will be sufficient to consider the three-phase case, in which a preliminary voltage of $\frac{1}{\sqrt{3}}$, or 59 per cent. of the normal, is thus obtained; producing a starting torque of

$\frac{1}{3}$ the full voltage value, or approximately 42 per cent. of normal fu
load torque. This form of starter is hence only applicable when
load is certain not to demand more than this amount of starting eff
Except for this limitation, the star-delta apparatus is a most sa
factory type. There is no loss of power, and therefore no heati
Any number of starts can be made in quick succession without
dangering any part of the equipment. The apparatus is comparativ
simple, consisting usually of a drum type of switch, having nine fing
for effecting the change of connexions, and also in most cases th

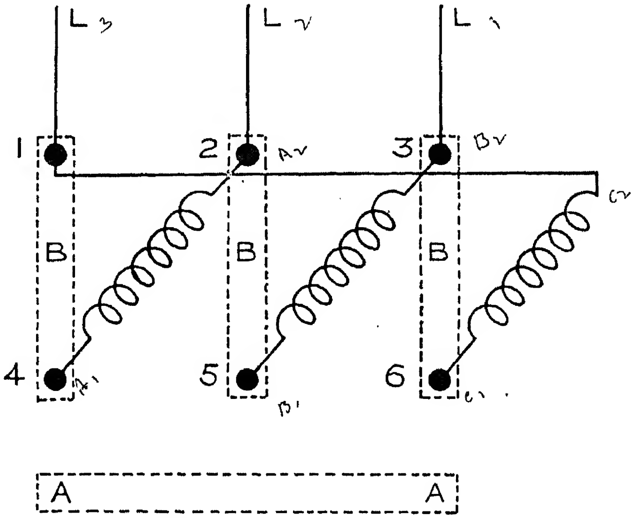



*Fig.* 47. Simple diagram of star-delta starting switch.

more for cutting out or changing the fuses or overload trips wl
starting, to cope with the extra heavy current at that stage.
The principle of the switch is indicated in Fig. 47, where the sta
windings of the motor are represented as being connected diagon
between three pairs of contact fingers, 1 and 6, 2 and 4, 3 and 5. I
be supposed that the three upper contacts are connected to the li
then a star connexion is provided by bridging contacts 4, 5, and 6
a transverse contact bar *AA*, and a delta connexion is given by join
1 to 4, 2 to 5, and 3 to 6, by means of three parallel drum sect
*BBB*; as illustrated by the dotted components in the figure.
fingers only are involved in the above scheme; but three others
added to disconnect the ends of the windings at 1, 2, and 3 from
line in the 'off' position, and three more for dealing with the cut-ou
The fixed contacts are variously mounted in practice on two, three,
four insulated finger-bars evenly spaced round the drum, the num
of sectors and therefore the width of the drum decreasing as the num

of bars increases. On the other hand, the dimensions of the complete starter at right angles to the axis are increased by multiplying the finger-bars, and the accessibility of the drum and contacts generally is reduced.

With regard to design details, the chief points that require attention are the length of the transition period, the return to the 'off' position, and the position of the overload devices in the circuit. These will be considered in turn.

When the connexions are being changed from star to mesh, it is necessary to open the circuit and reconnect it. The same procedure is involved in many, if not most, schemes for transformer starting. Unless the requisite attention is devoted to this open-circuit change-over, serious trouble will result; and the principles involved apply to any type of starting in which the current is broken and remade.

The leading characteristic of the normal squirrel-cage motor is the possession of a very low-resistance rotor, wound almost as inductively as possible. Such a winding will strenuously oppose any change in the flux passing through it. For example, when the stator is switched on to the line, the building up of the flux is resisted; and a large initial current flows, producing a relatively small torque. Similarly, when the flux has been created, its duration will be prolonged by the same cause after the stator circuit has been opened. The trouble occurs when the circuit is remade, unless the interval is so short that this persistent flux has not sufficient time to get seriously out of step with that corresponding to the reapplied E.M.F.

In order that the sequence of events may be understood, it should be realized that, together with the flux, both the rotating field and the back E.M.F. are prolonged for quite a considerable time after the line voltage has been cut off. For small motors, however, this period is much shorter than with large ones, since it consists of the time taken for the stored energy to be dissipated by the losses, of which the ohmic resistance of the rotor is the most important. As the size of the machine becomes greater, the resistance increases with the diameter, but the energy with the square of the diameter; and thus the effect is the more serious, the larger the motor.

The trouble would nevertheless be negligible if the back E.M.F. were in correct phase opposition to the impressed voltage when the circuit was reconnected. In default of special means for securing an instantaneous transition, however, this is not the case, and it is actually possible for the E.M.F. to have slipped by half a cycle during the interval, when the peak current may amount to four times that given by switching on with the rotor locked. Since this latter will be in the vicinity of six times the normal full-load current, it will be seen that the change-over peak may have a very large value indeed. An actual example that occurred in practice in connexion with an auto-transformer starter is quoted by Hellmund,[1] the motor being only 40 H.P. capacity, having a normal full-load current of 116 amperes at 70 per

[1] See 'Transient Conditions in Asynchronous Induction Machines', *Journal A.I.E.E.*, Feb. 1917, vol. 36, p. 321.

cent. power factor, 220 volts and 60 cycles. The locked-rotor curren was in this case 450 amperes, but the transition peak was 1,300 amperes or 11 times the normal working current. The futility of employing starter to reduce the starting current by about 60 per cent. when thi enormous rush can occur after starting should be evident at a glance.

The conclusions to be drawn from the above are: first, that th transition should always be effected as rapidly as is practicable; an secondly, that star-mesh starters are inadvisable for motors above given capacity, the limit in practice being about 30 H.P., this figure however, depending upon speed of transition and rotor resistance With regard to ensuring rapidity, there are a number of very ingeniou dash-pot and pendulum devices on the market which prevent the re connexion being made if the movement of the handle has been to slow. One by George Ellison may be quoted on account of the com

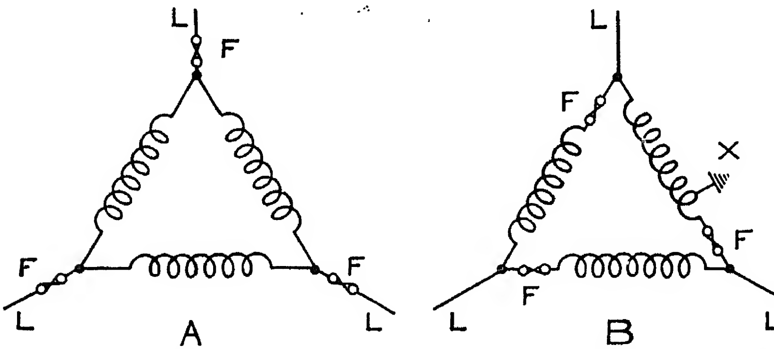



*Fig.* 48. Connexion of cut-outs (FFF) in a star-delta starter: A, correctly located B, incorrect, permitting burn-out of right-hand phase due to fault at X.

prehensive protection it secures. When the contact-drum is moved t the starting position, a spring is extended which begins pulling th plunger out of a dash-pot. No further movement can be made unt the plunger has reached the end of its travel; and, unless the drum b subsequently rotated with more than a given speed, an arm which ha been lifted bya cam on the operating shaft returns against the delay of th dash-pot acting in the reverse direction, and fouls the closing mechanism

With regard to the return of the drum to the 'off' position, there ar several alternative methods employed by different designers, as follows

(*a*) The starter rotates always in the same direction, viz. 'start 'run', 'off', 'start', 'run', &c.

(*b*) The moving contacts, after going in one direction to 'start' an then 'run', reverse in returning to 'off', passing throug 'start' on the way.

(*c*) The handle is moved in one direction to 'start' and in the re verse direction to 'run', passing through 'off' on the way.

It is undoubtedly the fact that a momentary current peak may b

caused if the moving contacts make the star connexion when returning rapidly to the 'off' position. The magnitude of the peak is usually not of great importance, but, other things being equal, it is preferable to adopt scheme (*a*) or (*c*) in preference to (*b*) on this account. Due consideration should be given to the fact that in scheme (*c*) the contacts have twice as far to travel as in (*b*), and are not in as favourable a position for rapid movement; so that the transition peak when starting may be much worse with the former.

It is somewhat more difficult to design the starter if the overload cut-outs are to be kept in the correct position when the motor is running, as shown at *A* in Fig. 48; the easier alternative being indicated at *B*, in which one end of each phase is left connected solidly to the line even after all the fuses or trips have operated. The latter expedient gives very defective protection against short circuits, and should not be used.

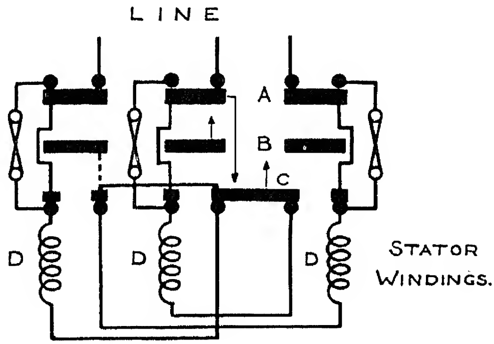
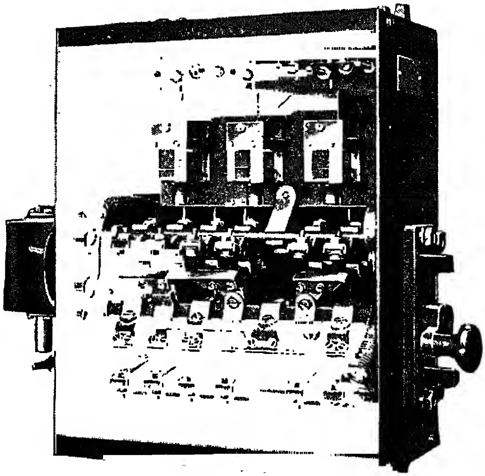


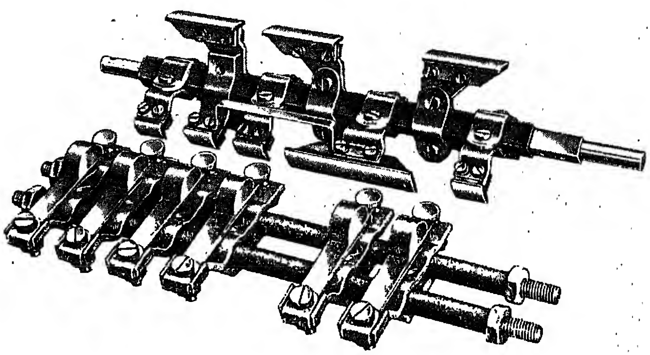

*Fig.* 49. Star-delta starter with provision for cutting-out fuses for starting; shown in start position.

An example of star-delta design is shown in Fig. 49, in which there are only two finger-bars, but three sets of sectors, *A*, *B*, and *C*, spaced round the drum cylinder at equal intervals of 120° so that *A* and *C* engage with the upper and lower sets of fingers respectively in the star position, and *B* and *A* in the delta; the direction of movement from one to the other being shown by the arrows. It will be seen that the three stator windings, *D*, *D*, *D*, have their lower ends 'starred' by the long *C* sector and the short one connected to it on the left; while the three *A* sectors connect the three phases of the line to the upper ends of the windings, short-circuiting the cut-outs. When the cylinder moves, the three *A* sectors join the terminals of *D*, *D*, *D*, in mesh, the fuse connexions coming from their junctions and through the *B* sectors to the line. The conductors short-circuiting the cut-outs are also moved away.

A view of the actual starter is shown in Fig. 50. The handle is first moved down to 'start' and then right up to 'run'; but a time element interlock prevents the final connexion from being made if too much time is absorbed over the change.



A



B

*General Electric Co., Ltd.*

*Fig.* 50. Star-delta starter. A. Complete. B. Cylinder and one finger-bar.

¶ REDUCING TRANSFORMER STARTERS.—The principle of the reducing transformer is a simple one, for it merely consists of interposing a step-down transformer between the line and the stator for starting purposes. Since the ratio of transformation is small, the auto-transformer is the more economical form to employ. Starting units being in addition of comparatively small size, it is usually an advantage to use the V or 'open delta' connexion, necessitating only two transformer windings instead of three.

This arrangement is indicated in the small diagram in Fig. 51, the larger giving the actual arrangement of the drum contacts. In both the starting or reduced-voltage position is shown, the running connexions

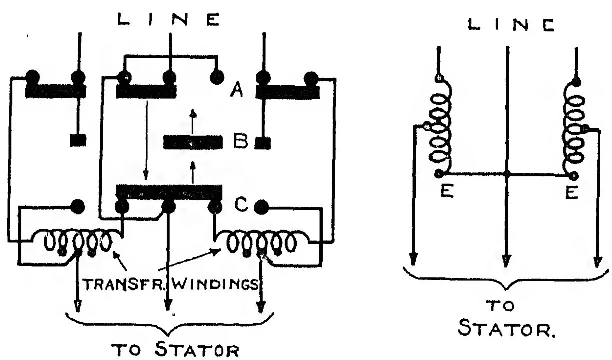



*Fig.* 51. Transformer-starter, with scheme of connexions; shown in start position.

being obtained in the smaller version by taking the outer stator leads direct to their respective line terminals and opening the connexion at *EE*.

The scheme embodied in the larger diagram has been made up out of the same drum-controller parts as were employed for the star-delta design in Fig. 49. The auto-transformer is shown below the starter, the secondary connexions coming from one of a number of alternative tapping points in order to adjust the starting voltage according to the torque required. It is most usual to provide for 40, 60, 70, and 80 per cent. of the full voltage; but it should be remembered in using the last that the power lost through the inefficiency of the transformer very nearly counteracts any gain due to the reduction of voltage. Thus, although the torque of the motor is considerably reduced, the interference with the line voltage is almost as great as if the motor were switched on direct without a starter.

In both the drum-controller diagrams that have just been given, a space is observable among the contacts that may at first sight appear unnecessary. This actually arises from the need of insulating adjacent sectors, which can only be conveniently accomplished by leaving a 'blank' opposite one of the supports on the shaft.

The 'auto-starter' that has just been described suffers from defect of the star-delta apparatus to which reference was made early the chapter, namely, that the circuit is interrupted during the transiti from 'start' to 'run'. Accordingly, this design is only suitable motors of smaller capacity than about 30 H.P.; and for larger mod a modified scheme is necessary. The most convenient for drum cc troller purposes is that indicated in Fig. 136, in which the transforn windings are disconnected at their inner ends as soon as the cylinc begins to move, and connected to the stator at the outer terminals the final position. During the transition the outer coils are in ser with the stator and function as reactances, providing a momentary int mediate step in the acceleration. When the running position is reach the same coils are short-circuited; but, since the other ends of t windings are disconnected, no induced currents are caused in them.

A further solution would be to let the starting and running connexio overlap for an instant, and to fit very much overrated resistances the transformer leads to prevent a heavy momentary rush of induc current in the portions of the windings short-circuited, as shown Fig. 134 in Chap. XIV.

¶ SYNCHRONOUS MOTORS.—There are two methods of starting sy chronous machinery, namely, that employing the auxiliary starting 'pony' motor, and that making use of the damper windings on tl field magnets, which function as a squirrel-cage arrangement when tl armature is connected to the A.C. mains and is thus caused to produ a revolving field.

The former method is much used when starting rotary converter and is also useful for synchronous motors when no great amount starting torque is required. The pony motor is designed with one pa of poles less than the main machine, in order to be able to reach the fu synchronous speed of the latter; and has about 15 per cent. of it horse-power. In order to facilitate synchronizing, the small machin must be designed with the correct slip to bring the main rotor ver gradually into phase. If it is of the wound-rotor type, the steps of th resistance starter would be graded close together at about this speed to give the necessary delicate regulation there. When synchronism i reached, the main running connexions are made.

Various means are employed for synchronizing the incoming machine It may be effected as with a generator, by exciting the D.C. field, an closing the main switch at the right moment, as indicated by a synchro- scope. Instead of using the latter, the armature only may be excite when it is rotating near synchronism, and it will pull into step with th assistance of its damper windings, whereupon the field circuit is als closed. Another method is to connect the pony motor in series with the main armature. About one-third of normal full-load current will flow at starting, and the machines will automatically accelerate to synchronism. As soon as steady speed is reached and the D.C. volt- meter has become quiescent, the starting motor is short-circuited.

The simpler method of running up to speed by means of the damper windings only is called 'tap starting' when applied to a rotary converter, since a reduced voltage is first applied to the stator by means of taps from the secondary of the main transformer. In the case of a plain self-starting synchronous motor a special auto-transformer is provided for the purpose, just as with an ordinary squirrel-cage motor. It is usual, however, to employ the full 'three-phase' winding instead

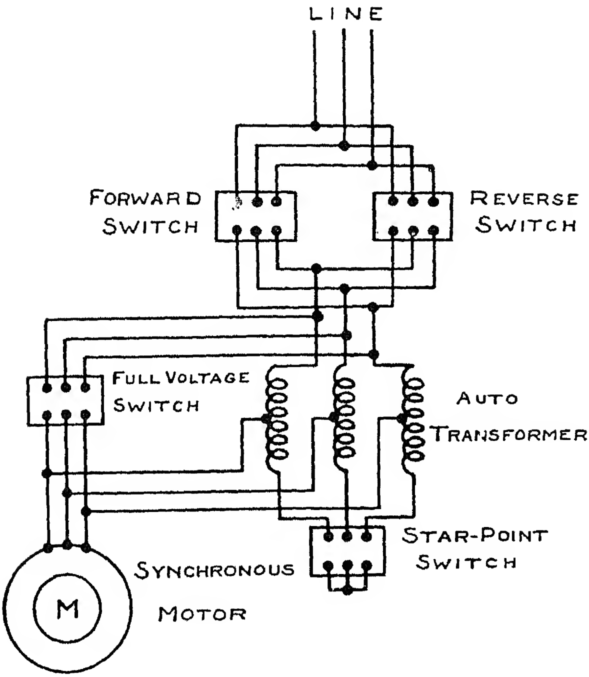
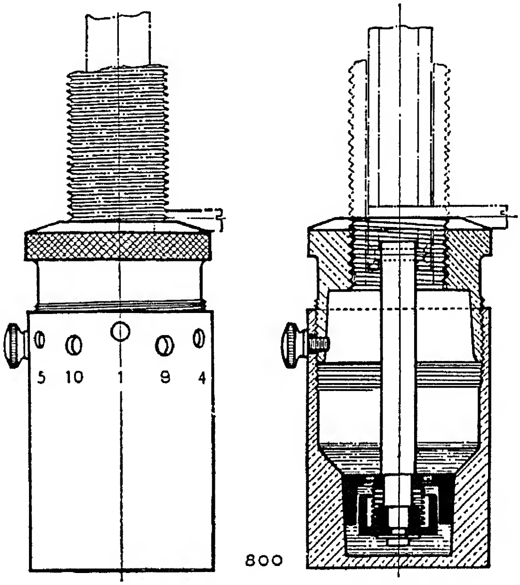



*Fig.* 52. Starting connexions for synchronous motor for forward and reverse running.

of the V-type; and duplicate line contactors or circuit-breakers are employed if it is necessary to provide for reverse running. The connexions are indicated in Fig. 52.

A slight extension of the foregoing method introduced by Korndorfer has resulted in smoother starting for these heavy machines. An additional switch is provided for disconnecting the neutral point of the transformer, and is opened at starting and also during transition from low to high voltage. At both stages, a part of the winding functions as a choking coil in each phase, charging the motor in the first case, and enabling the high-voltage switch to be closed before the starting circuit is broken in the second case.

¶ USE OF TIME LAGS.—Instead of employing switching means to hinder the operation of cut-outs during the starting of squirrel-cage motors, inverse time-lag devices can be attached to the overload trip coils, preventing the latter from operating instantaneously, but bringing about operation after a period which varies inversely as the overload. The oil dash-pot pattern made by George Ellison, shown in Fig. 53, possesses a cylinder with a short conical bore, and adjustment of the time lag is effected by screwing the dash-pot itself up or down, thus varying the clearance between the piston and bore, and also the length of stroke.




George Ellison.

*Fig.* 53. Double-rate time-lag device.

For the present purpose, however, the plain dash-pot will probably not interpose sufficient delay for the heavy starting peaks, and the section on the right of the illustration shows a special arrangement whereby the delay is much increased for over-currents exceeding five times normal. When the pull on the plunger is not sufficient to compress the spring the small by-pass valve is off its seating and permits extra leakage of oil to occur, giving the ordinary time lag; but the closing of the openings much reduces the leak. For overloads exceeding fifteen times normal both forms of dash-pot permit instantaneous operation.

This device is particularly useful when large motors are being started by means of oil switches.

# VIII

## SOLID RESISTORS

THE purpose of a resistor in connexion with electric control gear is to limit the flow of current by making its path more difficult. A variable resistor is thus the exact counterpart of a tap, cock, or throttle-valve in hydraulics ; for all of these interpose resistance into the path of the water by locally reducing the area of the duct, necessitating an increased velocity at the constricted part, accompanied by increased fluid friction and heat production. When the area is reduced to zero infinite resistance has been interposed and the water current ceases.

When an electric current flows through a resistance heat is also produced and must be dissipated in some manner. The method adopted for dealing with this waste heat is the principal factor that differentiates one design of rheostat from another, and that determines the desirable attributes of the resistant material. Whereas the heat produced is proportional to the product of the resistance and the square of the current flowing, or to the product of the current and the voltage drop in the resistance, the heat given out from the hot body is approximately proportional to the area of exposed surface multiplied by the temperature rise above the atmosphere. Under transient conditions, such as when the resistance is heating up during a starting period, the heat produced is not all given off, some being absorbed by the hot material in raising its temperature. This heat is measured by the product of the mass of the material, its specific heat, and the rise in temperature.

It is thus seen that there are two methods of disposing of the heat developed in a solid resistance, namely, by removal through atmospheric cooling and by storage. The latter method is that mostly employed for starters, and the former for controllers and regulators. Whereas a large heat capacity is a valuable feature in a starter, an extensive surface is important for continuous duty apparatus. In both it is an advantage to employ a resistant material that will stand a high temperature.

¶ REQUIREMENTS OF SOLID RESISTORS.—The requirements of an efficient resistor may now be summarized. In the first place, it must be compact ; for space and material are both valuable. This quality is given by the possession of a high resistivity. The latter is nowadays most frequently expressed in microhms per cm. cube, a unit which may be converted into microhms per inch cube by multiplying by 0·394.

Secondly, a resistor must be robust, that is, it must not be so soft or brittle as to become deformed or break under ordinary treatment ; and it is important that these qualities hold good not only when the materials are cold, but also when they are at the highest temperature to be attained in practice. At one time the only wires obtainable for resistance purposes were iron and a species of German silver that

became crystalline and therefore brittle after repeated heating. The iron, on the other hand, was apt to sag badly when hot; and in consequence the old rheostats frequently gave trouble.

Thirdly, the value of the resistance should vary as little as possible with temperature, otherwise the circuit conditions will be far from constant. A resistant material is therefore demanded with a low temperature coefficient.

Finally, it should resist corrosion to the greatest possible extent.

¶ RESISTANCE MATERIALS.—The materials available for resistors may be divided into metals and non-metals; while the former may be further classified as pure metals and alloys. In general, non-metals have a negative resistance/temperature coefficient, that is, the resistance falls as the temperature rises; while metals have a positive coefficient. The variation in the case of alloys is usually, however, much less than in the case of pure metals, while certain examples, such as constantan, have almost a zero coefficient, and others a small negative one.

Non-metallic solid resistors are practically confined to carbon and to mixtures containing carbon as their principal ingredient. This element exists in a number of commercial forms, the resistivities of the most useful being as follows:

TABLE 6. RESISTIVITY OF PURE CARBON

| *Form.* | *Resistivity Microhms-cm³.* | *Temperature Coefficient Unit Variation per 1° C.* |
|---|---|---|
| Graphite | 3,000 | |
| 'Retort' carbon | 4,000 to 7,000 | −0·052 |
| Arc-lamp carbon | 3,500 to 8,000 | |

Pure carbon is little used except for very high resistances, and then not often for control gear. Brazil has proposed a rheostat of carbon powder, with a container and a moving electrode, after the manner of a liquid starter. The compression type of pure carbon rheostat is, however, the only form that has been developed commercially, and this is used not only as a useful piece of laboratory apparatus, but as a starter for small motors, such as those driving fans. It consists of a pile of disks composed of gas carbon or of a thinner and more flexible form, through which the current flows. The resistance across the numerous junctions is very considerably altered by compressing them into closer contact, and this is done by means of a screw. The adjustment is continuous, constituting one of the chief advantages of the type.

Resistance units are made in the form of rods about ¾ in. in diameter, composed of carbon powder united by means of a binder such as tar. By a suitable proportioning of the mixture a wide range of resistance may be obtained, varying from about 15 to 500 ohms per inch. They are chiefly employed with lightning arresters, fuses, and similar apparatus. One of their drawbacks is the burning of the binder and the alteration or destruction of the unit if the temperature is allowed to exceed about 150° C.

A more robust and mechanical mixture, forming the basis of the 'Silite' resistance, consists of silicon carbide with free silicon and carbon, together with a high-temperature binder. These units can be used even up to a red heat. They are of comparatively recent introduction, and their robustness and negative coefficient may find them appropriate employment in control work.

¶ METALLIC RESISTORS.—The outstanding advantage of metal as a resistance material is its strength, which enables it to be shaped so as to offer a large cooling surface to the atmosphere. The various forms in which it may be built up are as follows : (1) wires and strips, coiled or bent to economize in space ; (2) networks, including expanded metal and woven 'grids' ; (3) grids, usually of cast, stamped, or bent iron.

Of the above the wire coil was the earliest, and is still employed for the great majority of small and moderate-sized rheostats. Its simplest variety consists of a helix formed by winding the wire tightly upon a mandrel, and then stretching it out until the spaces between turns are equal to the diameter of the wire itself. Such 'open spirals', to give them their popular designation, are sufficiently self-supporting only when their lengths and internal diameters are not excessive for the thickness of wire in question. Rules are in existence for determining these dimensions that give a very shaky and imperfect result. In the opinion of the author no open coils should be used the dimensions of which much exceed the values given below.

TABLE 7. DIMENSIONS OF OPEN RESISTANCE COILS

| *S.W.G.* | *Mandrel Diameter.* *In.* | *Length of Open Coil.* *In.* |
|---|---|---|
| 9 to 13 | $\frac{1}{2}$ | 14 |
| 10 to 16 | $\frac{3}{8}$ | 12 |
| 14 to 19 | $\frac{1}{4}$ | 10 |
| 17 to 24 | $\frac{1}{8}$ | 8 |

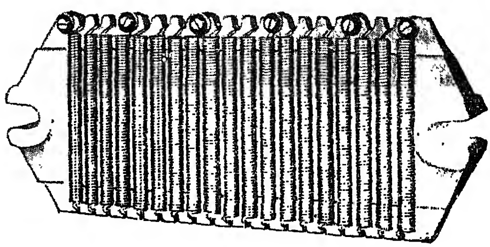
Wires thicker than No. 9 are difficult to coil on a winding lathe, and those thinner than No. 24 should not be used as open coils. It is good practice to connect from two to four single coils in parallel as the equivalent of one thick resistor.

There are a great many ways of supporting bare spirals, of which the following are examples :

Winding the continuous length of coil round a notched slab of asbestos board or porcelain (especially useful for the smallest coils as in Fig. 54) ; passing the ends through perforations in slabs of insulation fixed opposite each other, the last turn at each end being bent slightly out of line to prevent it from being pulled through ; attaching the coils at each end to porcelain bobbins screwed or bolted to steel strips forming part of a frame or structure ; passing the spirals over bobbins threaded on parallel steel rods, supported by strips in a frame or structure.

The open spiral is able to cool more rapidly by atmospheric convection and radiation than any other form, and it is therefore especially suited for controllers. Supporting it in contact with a solid renders it capable of withstanding a higher momentary overload ; but after being in circuit for the specified period, the unit must have a prolonged interval for cooling.

Solid support may be afforded either externally or internally. For the former the coils may be laid in troughs of earthenware or other incombustible substance, or embedded in sand or cement, being kept apart by strips of glass or other means. The internal method is, however, usually employed to-day, consisting of winding the wire on tubes or bobbins of insulating material. Asbestos is generally used for the cheaper units, and plain or grooved porcelain or pottery for the more expensive ; while solid strip mica has recently come into very successful use, and is comparatively low-priced. Two examples are shown in



*Metropolitan-Vickers Electrical Co., Ltd.*

*Fig.* 54. Porcelain block resistance unit.

Fig. 55, consisting of a plain porcelain tube wound with very fine wire, which is afterwards covered with bakelite varnish capable of withstanding temperatures up to 200° C ; and an asbestos resistance tube, having small porcelain bushes at the ends to fit into drilled strips. It should be borne in mind that adjacent turns of a helix carrying a current attract each other, and that if they are not wound tightly in the first case, or coated with varnish in the second, they will slide along their support and bunch themselves. The asbestos pattern is very suitable for starters and regulators, the rating of a tube 5 in. long by $\frac{3}{4}$ in. in diameter varying from about 0·45 ohm and 7 amperes continuously to 10 ohms and 0·4 ampere. The porcelain type is adapted for much higher resistances ; 5,800 ohms, passing 0·8 ampere continuously, having been attained by the author on a 1-in. bobbin 6 in. in length, with a single layer, and 9,000 ohms and 0·06 ampere by means of a three-layer winding. Such resistors as the latter are suitable for connecting in series with relay or contactor coils.

Metal strip may be wound in the same form as wire. A very neat and efficient type of rheostat consists of a zigzag strip embedded in strong enamel on one side of a ribbed cast-iron plate. This is one of

the most robust designs of rheostat; but unfortunately it is extremely difficult to repair when even slightly damaged, such as might be the result of an overload.

Compactness is attained in the second and third type of solid resistor by the adoption of a flat, rectangular shape, the sheet formation being intersected and corrugated to present a large cooling surface. Resistors in the form of nets may be composed of expanded sheet metal or ordinary wire netting, the latter being sometimes employed for temporary purposes, such as when testing large generators on site, by winding a considerable length in zigzag fashion over and under two parallel rows of insulated rods or pipes.

A development of this method that is of manufacturing utility is the network grid, in which the strands running in one direction are com-

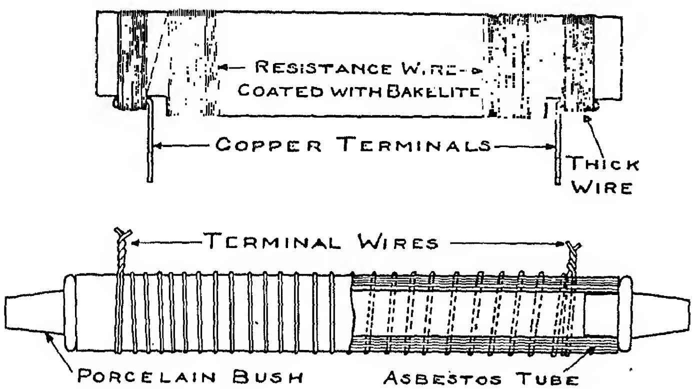
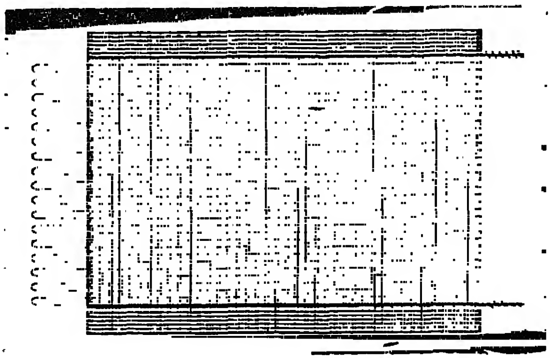



*Fig.* 55. Two resistance units: the upper of porcelain, the lower of asbestos.

posed of high-resistance wire or strip; and those in the other are formed of strongly woven asbestos impregnated after fabrication with a silicate that serves to consolidate and protect the fibrous material. Such units are provided when desired with connecting lugs for assembly in a rectangular framework just like the regular cast-iron grids. The author has tested samples of these quite severely and has found them unaffected by continuous temperatures as high as 300° C. A representative example is shown in Fig. 56.

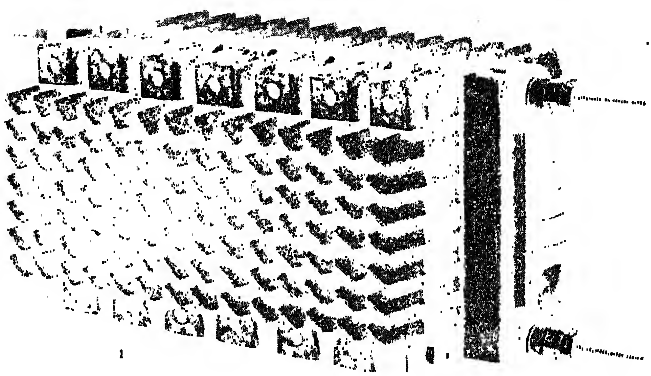
The units that have been so far described are not capable of dealing with currents much exceeding about 50 amperes, with the exception of the expanded metal type and the wire netting. For such heavier amperages the regular grid is almost compulsory, in one of its various forms. The original material was cast iron, and this is still employed for the great majority of purposes, being included, for example, in Figs. 31 and 167. It is cheap and of high specific resistance, that of the usual qualities ranging from 75 to 100 microhms per cm. cube. As generally designed, it possesses slotted lugs at either end and in the

middle, all of which are available for connexion taps, though the middle one is nearly always used for supporting purposes only. The grids are



*Cressall Manufacturing Co*

*Fig.* 56. Network grid.

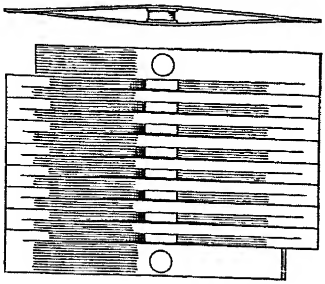


*Rheostatic Co.*

*Fig.* 57. Sheet steel grids, showing spacers projecting at top.

simply dropped in place upon three round bars covered with micanite, and the set is clamped tight by means of nuts on the ends of the bars when all are assembled. Mica washers separate the lugs that are not required to be in electrical contact.

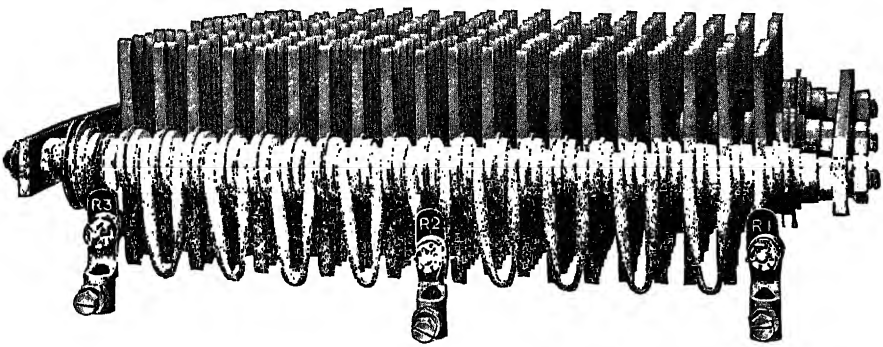
Such grids are capable of enduring a temperature rise as high as 350° C. continuously, though for short periods of a minute or so a considerably higher mark can be attained. The softening temperature of the iron forms the upper safe limit as far as this part of the apparatus is concerned, being a cherry-red heat, or about 600° C.; but the insulation under the lugs is carbonized at a temperature of about 175° C., which may be reached if the first-named temperature be exceeded for any considerable period. Breakage need not be feared with a stationary installation if ordinary treatment is accorded; but for cranes and other moving or portable equipments some form of mild steel grid is usually better.



*Rheostatic Co.*

*Fig.* 58. Diagram showing formation of grid in Fig. 56 out of sheet metal by splitting and insertion of insulated spacer.

The material known as 'No-mag' cast iron offers certain advantages over the ordinary quality. First, it has a specific resistance of 140, or about 50 per cent. more than the ordinary iron. Secondly, its resistance is more constant, the temperature coefficient being 0·0009 in place of 0·0019. Thirdly, it is less brittle, its Izod test figure being 29 ft.-lb. as compared with 14 ft.-lb. It is, however, more expensive.




*Electro-Mechanical Brake Co., Ltd.*

*Fig.* 59. Continuous unbreakable grid resistor.

Two examples may be given of the mild steel grid. The first of these, illustrated in Fig. 57, is made by the Rheostatic Co., and is formed by slitting rectangular plates without removing any material, the sheet being cut to form a single long conductor. A mica-insulated metallic spacer strip is then threaded between adjacent bars, as shown in Fig. 58, displacing them and separating them electrically, and forming a rigid arrangement.

In contrast to this, the E.M.B. pattern is constructed by winding a mild steel ribbon in the form of a grid, as shown in Fig. 59. The result is robust, compact, and generally satisfactory; but the necessity for hand-manufacture renders the type somewhat expensive. The cost is, however, not so high as to outweigh its advantages in many situations.

The use of mild steel brings about a saving in weight, for the resistivity (including medium steel) is at most one-fourth that of cast iron, while the greater strength enables much thinner metal to be employed. This again is in favour of its use for portable apparatus.

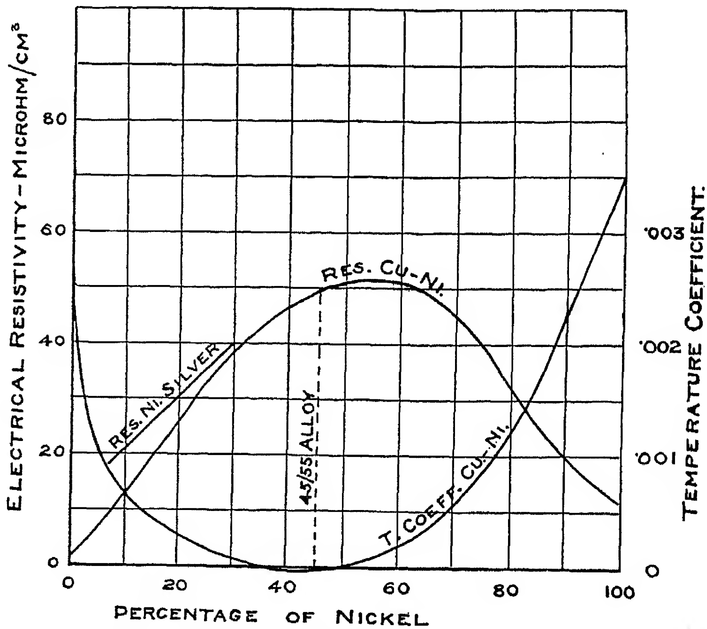



*Fig.* 60. Electrical properties of copper-nickel alloys.

¶ Liquid Immersion.—The flow of heat from a resistor may be very much increased by immersion in water or oil. The former is the liquid with the greatest specific heat, and it can therefore exert the greatest possible cooling effect. Water immersion applied to an existing resistor approximately quadruples its current-carrying capacity, and if it were not for the very great difficulty that is experienced in preventing deterioration of metals and insulation through oxidation and damp the practice would be widely adopted. It is at present only employed for temporary purposes, when it is possible to remove and dry the resistors immediately after use.

Fortunately oil immersion does not possess these defects, neither is it subject to evaporation, and it has thus become a standard method in

resistor design. The effect is nearly as great as that of water tests made by the author with transformer oil and resistance wires indicating that about three times the current was needed to fuse the wire under oil as was required in air. Liquid immersion without provision for cooling the oil is, however, a method of storing and not dissipating the heat; and it is of most value for starters, for which it is chiefly used. An example is shown in Fig. 17.

¶ RESISTANCE METALS.—Considerable research has been carried out during the past two or three decades as regards suitable alloys for resistance purposes. The most valuable step has been the adoption of nickel as a material, and the possibility of obtaining this metal, as well as copper, in a state of great purity has enabled considerable advances to be made in the design of rheostat windings. Similar work in connexion with metallic chromium has formed the latest phase of the subject, and has recently opened up a new range of alloys with remarkable properties.

Among others, the nickel silvers (or German silvers) have been improved as the result of investigation. These are composed of copper, nickel, and zinc, the proportion of the second constituent varying from 7 to 30 per cent. in the classes suitable for resistors. The variation of the resistivity of these with nickel content is given in the short curve in Fig. 60. But the most commonly used alloys are binary intermixtures of nickel with copper and chromium respectively. The former are employed for resistors working at temperatures up to about 300° C., and have a resistivity of about 50; while the latter are the materials *par excellence* for heating elements for use up to about 900° C., and have resistivities approximating to 100.

Besides these, a copper-nickel-manganese alloy should be mentioned with electrical properties resembling the binary copper-nickel, but with an unusually persistent tensile strength at temperatures up to 450° C. Whereas ordinary brass (60/40) falls off from 31·49 to 3·92 tons per sq. in. as regards this quality over the above range, the alloy in question gives results represented by 40·7 and 40·6 respectively. Particulars of the most interesting metals are given in the following table:

TABLE 8. PHYSICAL DATA REGARDING RESISTANCE METALS[1]

| *Alloy or Metal.* | *Ingredients.* | *Composition. Per cent.* | *Melting Point. ° C.* | *Resistivity Microhms per cm³.* | *Temp. Coeff.* | *Tensile Strength. Tons sq. in.* 20° C. | 450° C. |
|---|---|---|---|---|---|---|---|
| Copper | Cu. | 99·5 pure | 1,083 | 1·7 | 0·00393 | 16·7 | 7·5 |
| Copper-nickel | Cu. : Ni. | 60 : 40 | 1,260 | 47 | 0 | 32·1 | 23·9 |
| (Constantan) | | 55 : 45 | 1,100 | 50 | 0 | | |
| Nickel-chrome | Ni. : Cr. | 80 : 20 | 1,560 | 105 | 0·00019 | 50 | 45 |
| Nickel-copper-manganese | Ni. : Cu. : Mn. | 70 : 26 : 4 | — | 50 | 0·00066 | 40·7 | 40·6 |

The above three alloys are all proof against corrosion from the atmosphere or from likely sources. Nickel-chrome wire alone is dark, the

[1] The author is indebted to Messrs. Henry Wiggin & Co., Birmingham, for much of the data regarding resistance alloys.

TABLE 9. COPPER AND

| S.W.G. | Diameter. In. | Area. Sq. mils. (0·000001 sq. in.). | $d^{\frac{3}{2}}$ in. | Resistance in Ohms per ft. Copper at 16° C. | Copper-nickel. | Nickel-chrome at 400° C. |
|---|---|---|---|---|---|---|
| 10 | 0·128 | 12,868 | 0·046 | 0·000623 | 0·0174 | 0·0404 |
| 11 | 0·116 | 10,568 | 0·039 | 0·000758 | 0·0215 | 0·0495 |
| 12 | 0·104 | 8,495 | 0·034 | 0·000944 | 0·0268 | 0·0616 |
| 13 | 0·092 | 6,648 | 0·028 | 0·001206 | 0·0341 | 0·0787 |
| 14 | 0·080 | 5,027 | 0·023 | 0·001595 | 0·0451 | 0·104 |
| 15 | 0·072 | 4,072 | 0·0194 | 0·001968 | 0·0556 | 0·128 |
| 16 | 0·064 | 3,217 | 0·0162 | 0·002493 | 0·0705 | 0·161 |
| 17 | 0·056 | 2,463 | 0·0133 | 0·003254 | 0·0922 | 0·211 |
| 18 | 0·048 | 1,810 | 0·0105 | 0·00443 | 0·125 | 0·288 |
| 19 | 0·040 | 1,257 | 0·0080 | 0·00638 | 0·180 | 0·414 |
| 20 | 0·036 | 1,018 | 0·0068 | 0·00787 | 0·225 | 0·510 |
| 21 | 0·032 | 804 | 0·0057 | 0·00997 | 0·257 | 0·645 |
| 22 | 0·028 | 616 | 0·0047 | 0·01302 | 0·369 | 0·844 |
| 23 | 0·024 | 452 | 0·0037 | 0·01771 | 0·503 | 1·15 |
| 24 | 0·022 | 380 | 0·0033 | 0·02108 | 0·598 | 1·37 |
| 25 | 0·020 | 314·2 | 0·0028 | 0·02551 | 0·723 | 1·66 |
| 26 | 0·018 | 254·5 | 0·0024 | 0·03149 | 0·892 | 2·05 |
| 27 | 0·0164 | 211·2 | 0·0021 | 0·0379 | 1·08 | 2·46 |
| 28 | 0·0148 | 172 | 0·0018 | 0·0466 | 1·32 | 3·02 |
| 29 | 0·0136 | 145·3 | 0·00159 | 0·0552 | 1·56 | 3·58 |
| 30 | 0·0124 | 120·8 | 0·00138 | 0·0664 | 1·88 | 4·33 |
| 31 | 0·0116 | 105·7 | 0·00125 | 0·0758 | 2·15 | 4·95 |
| 32 | 0·0108 | 91·6 | 0·00112 | 0·0875 | 2·48 | 5·68 |
| 33 | 0·0100 | 78·5 | 0·00100 | 0·1020 | 2·89 | 6·61 |
| 34 | 0·0092 | 66·5 | 0·00088 | 0·1206 | 3·47 | 7·87 |
| 35 | 0·0084 | 55·4 | 0·00077 | 0·1446 | 4·10 | 9·39 |
| 36 | 0·0076 | 45·4 | 0·00066 | 0·1767 | 5 | 11·5 |
| 37 | 0·0068 | 36·3 | 0·00056 | 0·2207 | 6·26 | 14·3 |
| 38 | 0·0060 | 28·3 | 0·00046 | 0·2834 | 8·03 | 18·3 |
| 39 | 0·0052 | 21·2 | 0·00038 | 0·377 | 10·7 | 24·6 |
| 40 | 0·0048 | 18·1 | 0·00033 | 0·443 | 12·6 | 28·8 |
| 41 | 0·0044 | 15·2 | 0·00029 | 0·527 | 15 | 34·3 |
| 42 | 0·0040 | 12·6 | 0·00026 | 0·638 | 18·1 | 42·3 |
| 43 | 0·0036 | 10·2 | 0·00022 | 0·787 | 22·3 | 51·1 |
| 44 | 0·0032 | 8 | 0·000181 | 0·996 | 28·5 | 65·1 |
| 45 | 0·0028 | 6·2 | 0·000148 | 1·302 | 36·8 | 84 |
| 46 | 0·0024 | 4·5 | 0·000118 | 1·771 | 50·6 | 116 |
| 47 | 0·0020 | 3·1 | 0·000089 | 2·551 | 73·5 | 168 |

RESISTANCE WIRE TABLE

| Current at 1,000 amperes per sq. in. | Current Capacity of Copper Wire I.E.E. Standard. | Current Capacity of 3/8″ Open Spiral, 1″ long. | | | | | S.W.G. |
|---|---|---|---|---|---|---|---|
| | | Copper-nickel. | | Nickel-chrome. | | | |
| | | 100° C. | 300° C. | 100° C. | 400° C. | 800° C. | |
| 12·87 | 35 | 20 | 41 | 16 | 35 | 69 | 10 |
| 10·57 | 32 | 18 | 36 | 13 | 30 | 56 | 11 |
| 8·495 | 28 | 15 | 29 | 11 | 25 | 49 | 12 |
| 6·648 | 23 | 12 | 24 | 8·8 | 20 | 41 | 13 |
| 5·027 | 19 | 9·2 | 19 | 6·5 | 16·5 | 33 | 14 |
| 4·072 | 16·3 | 8·5 | 16 | 6 | 14 | 29 | 15 |
| 3·217 | 12·9 | 7·1 | 14 | 5 | 12 | 25 | 16 |
| 2·463 | 9·8 | 5·6 | 11·5 | 4 | 10 | 19 | 17 |
| 1·810 | 7·2 | 4·3 | 9 | 3 | 8 | 15 | 18 |
| 1·257 | 5·3 | 3·7 | 6·7 | 2·6 | 5·7 | 12 | 19 |
| 1·018 | 4 | 3 | 5·8 | 2·1 | 4·7 | 10 | 20 |
| 0·804 | 3·3 | 2·7 | 5 | 1·9 | 4·2 | 8·7 | 21 |
| 0·616 | 2·5 | 2·3 | 4·2 | 1·6 | 3·5 | 7·8 | 22 |
| 0·452 | — | 1·8 | 3·2 | 1·3 | 3 | 5·2 | 23 |
| 0·380 | — | 1·6 | 2·9 | 1·1 | 2·5 | 4·8 | 24 |
| 0·314 | — | 1·4 | 2·6 | 1 | 2·1 | 4·5 | 25 |
| 0·254 | — | 1·3 | 2·2 | 0·90 | 1·9 | 3·7 | 26 |
| 0·2112 | — | 1·2 | 1·9 | 0·85 | 1·7 | 3·3 | 27 |
| 0·1720 | — | 1·1 | 1·6 | 0·72 | 1·5 | 2·8 | 28 |
| 0·1453 | — | 1 | 1·4 | 0·60 | 1·3 | 2·4 | 29 |
| 0·1207 | — | 0·82 | 1·3 | 0·53 | 1·1 | 2 | 30 |
| 0·1057 | — | 0·72 | 1·1 | 0·50 | 0·90 | 1·8 | 31 |
| 0·0916 | — | 0·68 | 1 | 0·45 | 0·80 | 1·6 | 32 |
| 0·0785 | — | 0·56 | 0·87 | 0·40 | 0·72 | 1·5 | 33 |
| 0·0665 | | | | | | | 34 |
| 0·0554 | | | | | | | 35 |
| 0·0454 | | | | | | | 36 |
| 0·0363 | | | | | | | 37 |
| 0·0283 | | | | | | | 38 |
| 0·0212 | | | | | | | 39 |
| 0·0181 | | | | | | | 40 |
| 0·0152 | | | | | | | 41 |
| 0·0126 | | | | | | | 42 |
| 0·0102 | | | | | | | 43 |
| 0·0080 | | | | | | | 44 |
| 0·0062 | | | | | | | 45 |
| 0·0045 | | | | | | | 46 |
| 0·0031 | | | | | | | 47 |

colour being due to a superficial oxide that serves as a protection to the metal. This alloy preserves its tensile strength to an eminent degree up to a temperature of about 900° C., but it may be used up to 1,000° C. continuously and has been known to withstand 1,200° C. for short periods without break-down. It is employed for small resistance units requiring a very high resistivity.

All are characterized by very low resistance/temperature coefficients as compared with copper. Copper-nickel is remarkable in this respect, as its coefficient is zero or even slightly negative over the range of alloys quoted. The variation of resistivity and temperature coefficient of all the binary copper-nickel alloys is given in Fig. 60.

¶ Design of Resistors.—The determination of the exact size of resistance wire or strip to employ under a given set of conditions is a matter of great difficulty without some form of preliminary experiment. In addition to the wide variations of operating duty, the proximity of the individual resistances to one another, the ventilation of the containing box, and a host of other conditions will affect the question considerably. By far the surest plan is to find by actual trial the performance of a single size of wire under the desired conditions, whereupon the characteristics of any other size of the same wire may be easily calculated from Preece's formula—

$$I = ad^{\frac{3}{2}};$$

which holds good not only for the melting-point, but also for any other limiting temperature if the coefficient $a$ be regarded as constant only for a given temperature. For example, if a wire, size $d$, will pass $I$ amperes safely under any given conditions, then another of size $d'$ will pass $I \times \left(\frac{d'}{d}\right)^{\frac{3}{2}}$ under the same conditions. This relationship will illustrate the fallacy of the method sometimes prescribed of designing resistance wires to carry so many amperes per sq. in. of section; whereas the amperage is not proportional to the area, that is, to the square of the diameter, but to the $(\frac{3}{2})$th power of the diameter.

An approximate idea as to the current-carrying capacity of typical resistance wires may be obtained from the table on pp. 100 and 101, which is calculated for single open spirals and continuous duty. Particulars of the standard wire gauge sizes are also given, with the values of $d^{\frac{3}{2}}$ to facilitate easy calculation.

It is important that the data as to current-carrying capacity be employed as a rough guide only, as conditions are so varied in different designs of rheostat that each case must be considered on its own merits. In particular, the current capacity for resistance wires in the table is only that for open coils 1 in. long wound on $\frac{3}{8}$-in. mandrels and supported vertically in free air. Thus the proximity of other resistors, or anything else that restricts ventilation, reduces the carrying capacity.

On the other hand, intermittent duty will increase the safe value of the current, and the proportion of the total time during which it is flowing should be taken into account. The curves in Fig. 61 show the

rates at which a cast-iron grid rises in temperature when four different currents flow through it continuously, the temperature in each instance gradually reaching an upper limit by a logarithmic curve. If it were stipulated that the limit marked by any given horizontal line were not

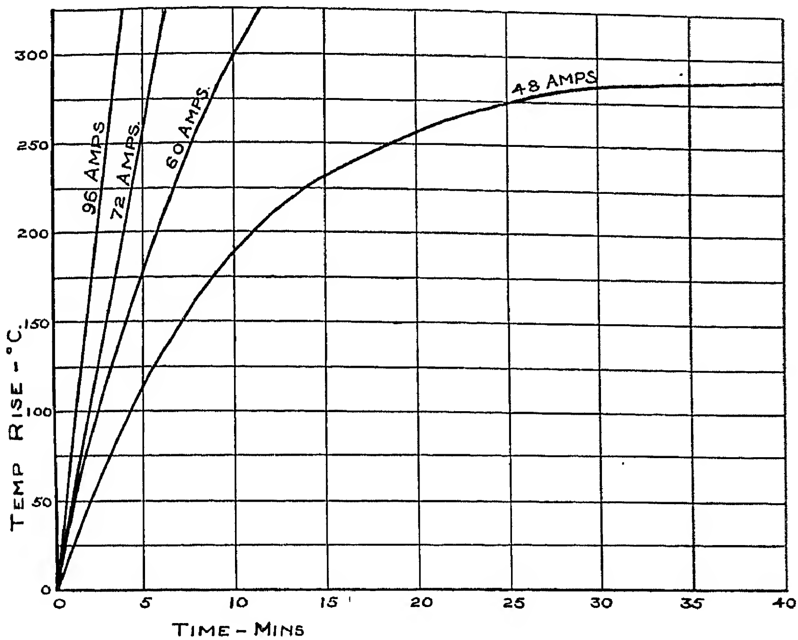



*Fig.* 61. Curves showing rate of heating of a standard cast-iron grid due to different currents.

to be exceeded, then the length of time during which any current could flow would be given by the horizontal intercept between the intersection of this line and the logarithmic curve appropriate to that current, and of the curve and the ordinate at the initial temperature. The periods of heating would then have to be followed by intervals of cooling, if the limit were not to be transgressed; and the above diagram indicates what a big change in the period may be caused by a comparatively small increase of the current.

# IX

## LIQUID RHEOSTATS

THE liquid rheostat is, as its name implies, a variable resistance in which the resistant material consists of a liquid, instead of a solid such as the wire spirals and iron grids that figure in the more usual form of regulating and controlling apparatus. It is essentially composed of two metallic electrodes separated by the liquid. These components may be situated within a metallic vessel, the inner surface of which actually forms one of the electrodes ; or the current may be led in and out by means of two or more quite distinct plates, the containing vessel simply functioning as such, and being composed of metal or of a non-conductor according to convenience.

Such a piece of apparatus possesses two outstanding advantages. In the first place, it is easily made up of cheap material ; and in the second it is able to carry the largest currents without risk of a serious breakdown. From these characteristics are derived its two principal uses, viz. as a temporary apparatus either for motor starting or control, or for absorbing large quantities of power during initial test runs, and on similar occasions ; and as a regular and permanent starter or controller for large motors. Since both the solid and liquid forms are frequently available for carrying out the same function, it will be of advantage to consider in some detail the characteristics of the former as compared with the latter.

First, the liquid rheostat is adapted for conducting safely and reliably the largest currents. The various designs of solid resistor, connected and disconnected from the circuit by means of sliding contacts, operate at a greater and greater disadvantage as the magnitude of the current increases. The use of contactors improves the situation somewhat, but at additional expense, which also increases rapidly with increase of current. It will be found, if the various difficulties in the design of large solid resistors be considered, that these are of small moment when a liquid resistor is substituted. The latter possesses a large storage capacity as compared with a coil or grid, and it is cheaply cooled, when the units are large enough to justify this, by means of water circulation, the piping, pump, and other items involved being unimportant for large powers.

Secondly, the liquid resistance possesses a maximum of reliability, since it is practically impossible to break it down. When a solid rheostat is sufficiently overstressed through the specified conditions being exceeded, it comes seriously to grief through overheating, even if it is of perfect design and construction. A single transgression of the limit of safety is capable of throwing the apparatus out of commission until the damaged part has been made good. In the case of the liquid rheostat, however, the result of misuse is simply that the liquid is made

to boil, and in nearly every case nothing further occurs. It is certainly a fact that the failures to which this apparatus is liable occur during ebullition, but they are extremely rare. Ordinarily, when the overload has been removed, the apparatus returns to its former condition and requires no attention to refit it for further service.

Thirdly, the acceleration is smooth, and does not demand a multiplicity of steps in order to avoid current peaks. The insertion of the electrodes into the electrolyte being a gradual process, the acceleration or retardation produced in the motor is also gradual. Thus not only are current and voltage peaks obviated, but the maximum safe rate of acceleration is obtained, and thus time can be saved without detriment to the motor.

Fourthly, this apparatus is simple to design and construct. A liquid rheostat is inherently robust, consisting chiefly of sheet-steel plates with a minimum of insulation. The ability to alter the specific resistance of the resistant material at will by varying its strength, and the absence of steps which require to have a definite relation to one another, permit great latitude in the proportioning of the various parts. There is no part of the apparatus which is subject to deterioration, and thus the principal difficulties of solid rheostat design and construction are absent.

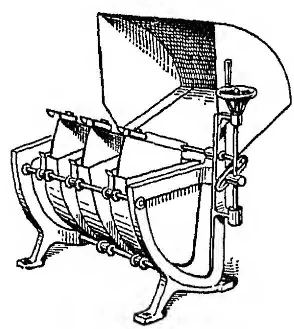
Against the above must be set a certain number of drawbacks. The most important of these is the variability of the resistance, which may become changed by evaporation, by rise of temperature, by alteration of the chemical concerned, by impurity, or by spilling. Secondly, the portability is inferior to that of at any rate the smaller patterns of solid rheostat, in that the liquid form does not admit of such easy mounting, or of the same treatment in connexion with a moving apparatus. Thirdly, the natural cooling of a hot liquid is considerably less effective than that of a set of spirals or grids, since not only is the temperature much lower, but the amount of surface is also relatively small. This is apt to render the liquid apparatus somewhat bulky for small powers where cooling by circulating pipes is not a paying proposition. Fourthly, it is sometimes difficult to cut the resistance out completely, and with many patterns it is customary to fit short-circuiting contacts which come into operation when the electrodes are in their all-in position.

The above defects are seen not to be of a serious nature, and to be only sufficient to turn the scale definitely against liquid rheostats for the smaller sizes. It is advisable, however, to keep them in mind when evolving a design.

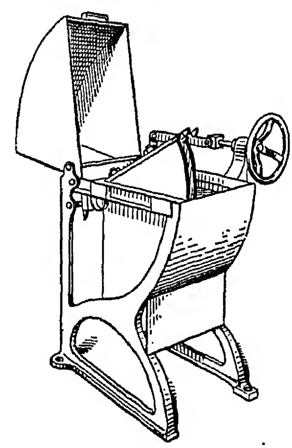
One of the principal sources of variability of electrolyte resistance is chemical action, which is able to alter the composition of the electrolyte, to erode the plates, and to produce quantities of gas. It should be recognized, however, that this only occurs to any appreciable degree with direct current, since the chemical actions are reversible, and what takes place in one half cycle is undone immediately afterwards. Thus chemical action has discouraged the use of liquid rheostats for controlling direct currents, and the large majority of units are employed in connexion with A.C. equipment.

¶ Types of Liquid Rheostat.—In common with other patterns of rheostats, the liquid forms may be broadly divided into starters and regulators. In the present case these are chiefly distinguished by being cooled naturally or artificially in the two cases respectively. Practically all the different types that will be described below can be used for either purpose, a starter being converted to a controller by the addition of water circulation. The following are the principal varieties of liquid rheostat in use :

*Temporary Rheostat.* For temporary purposes a rough liquid rheostat may be composed of a tub, either of wood or earthenware, containing two sheet-iron plates mounted on wood cross-bearers, or in some



Standard liquid rheostat for starting duty up to about 500 B.H.P.



Single-tank form of the rheostat shown in Fig. 62.

*Figs.* 62 and 63. Dipper type of liquid rheostat.

other convenient way. A solution of washing soda is employed as the electrolyte, the soda being mixed with a small quantity of water to form a strong solution, and being added gradually to the water in the tub until the desired results are given. Another method is to employ an iron vessel forming one electrode, the other consisting of a rectangular plate which is lowered into the liquid by means of a simple winch mechanism. When very high potentials are to be dealt with iron pipes immersed in plain water are used.

*Dipper Type.* The simplest form of regular apparatus is that in which a sheet-steel electrode is pivoted so that it may be either completely above the surface of the liquid, or gradually immersed in the latter ; the tank containing the electrolyte forming the other electrode. This pattern is made in the single-phase or single-pole form, when it consists of a single tank and dipper ; but it may be made two-phase or two-pole by the duplication of these elements. For three-phase

working three tanks and dippers may be used, or a single tank in conjunction with two insulated dippers.

Representative designs of these two patterns are shown in Figs. 62 and 63. The former may be employed as a 'straight through' rheostat by insulating the dippers from one another. Such a rheostat is employed, for example, in the leads of a phase advancer for starting purposes. Since most three-phase rheostats are used for gradually short-circuiting the rotor windings of an induction motor, the dippers are in general connected together.

This type is employed for motors up to about 600 H.P. At the upper end of the scale it is the custom to use more than a single tank per

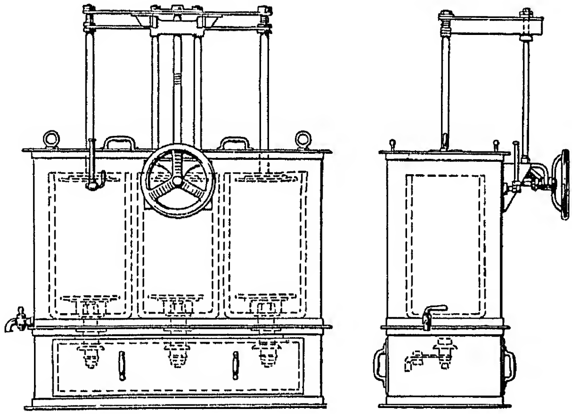


*Fig.* 64. Liquid rheostat for starting duty with motors up to about 2,000 B.H.P.; embodying earthenware pots (shown dotted).

phase. For the smaller units a single dipper is used per tank, but th larger have two, which are comparatively far apart along their uppei edges, but approach each other towards the lower extremities. The result is that as they are moved downwards, not only is a greater area of each electrode immersed, but the distance between the latter and the sides of the tank is decreased.

It is not good practice to make the dippers touch the tank when they are in their final position, as the degree of contact would be very doubtful. In order to cut out all the resistance small laminated contacts are attached to the moving elements, which meet copper or brass flat contacts fixed to the tank. A cover is usually supplied for this form of apparatus to protect it against the intrusion of debris. Ventilation is provided for by the use of perforated metal for at any rate the curved portion; but even this can be made solid if the situation is exposed to a dust-laden atmosphere.

The dipper type of rheostat does not lend itself very well to artificial cooling, and it is therefore generally used for starting service only.

*Triple-pot Type.* For motors exceeding about 500 H.P. and up to about 2,000 H.P. the type shown in Fig. 64 is most used. This possesses a single tank, containing three pots, usually of vitrified earthenware, separating the phases. A flat pattern of fixed contact is located at the bottom of each of these pots and a corresponding moving electrode is provided for each, these being connected to a cross-beam which

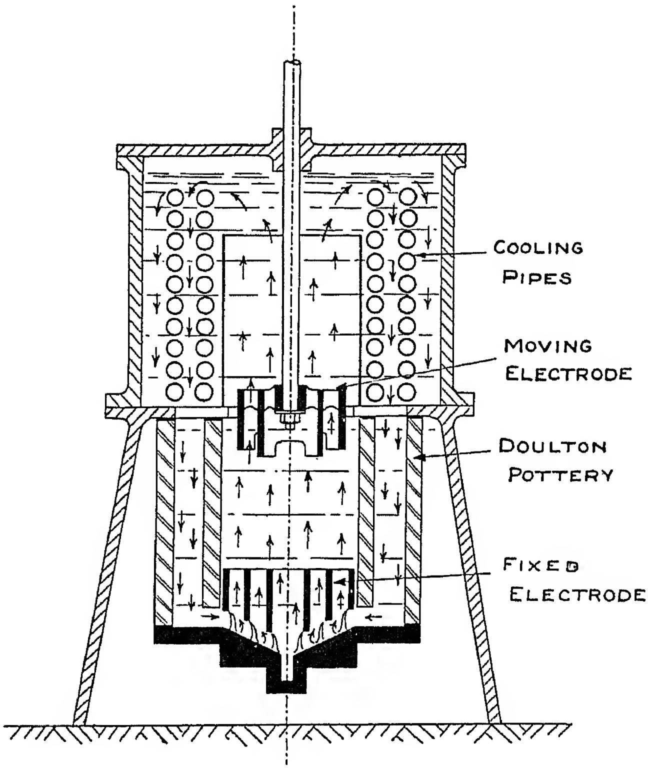



*Fig.* 65. One phase of triple-pot rheostat by Messrs. Allen West.

can be raised or lowered by means of the hand-wheel and worm gear illustrated.

The principal defect of this form arises from the risk of breakage of the pots caused by mechanical shock due to faulty adjustment of the electrodes, or by exposure to extremes of temperature. There is no doubt that total immersion in the liquid minimizes the heat effect, and the pattern shown should therefore be definitely better than the form in which the pots are exposed to the atmosphere on the outside. To guard against the risk of fracture in the latter, treated wood or enamelled steel are sometimes used.

A further defect is that circulation is not very thorough, as there is usually no orifice at the lower ends of the pots. No strong reason, however, exists why this should not be provided, as such a rheostat is not required to have infinite resistance in the full open position, being merely intended to start or regulate an induction motor by varying the resistance of the rotor circuit from a definite fairly high value down to that of the rotor only. A design where provision is made for a through current of liquid is shown in Fig. 65. Since it is not a requirement that the phases should be electrically separate, care should be taken not to make the pots exceed their function as insulators.

This form of rheostat can be employed as a controller by the addition of circulating pipes either round the pots or above them. It is the

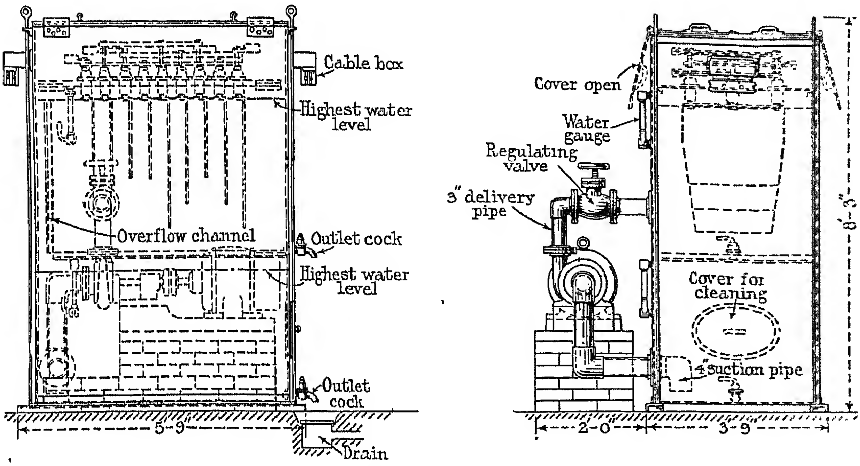



*Fig.* 66. Centrifugal-pump type of rheostat, designed for a 3,000 B.H.P. motor.

usual pattern for use as a liquid slip regulator, the moving electrodes being suspended by means of the lightest possible links from light arms attached to the shaft of a torque motor. The same rheostat is made to do duty as a starter when beginning work by the provision of a hand-wheel similar to that shown in Fig. 64.

*Rising Liquid Type.* The largest motors, up to and exceeding 3,000 H.P., are started and controlled by means of what is known as the rising liquid type of rheostat, an example of which is shown in Fig. 66. In this the electrodes are fixed, and the level of the liquid is raised by a centrifugal pump, thus gradually immersing the plates. When used as a starter the apparatus is operated by means of a single lever which has three positions, one of which is ‘ off ’. At ‘ start ’ the pump motor is set in motion, and gradually fills the rheostat tank with electrolyte from the lower chamber. Thus the main motor is gradually accelerated, the apparatus having an inherent time element fixed by the capacity of

the pump. Upon full speed being reached, the handle is thrown to the final or running position, when the electrodes are short-circuited by an oil-immersed drum pattern switch, and the pump motor is stopped, the electrolyte being thereby permitted to drain away from the upper tank. An interlock is usually provided to prevent the handle being moved on to the final position until the main motor has attained a given speed.

When employed for continuous working, this last form of rheostat is artificially cooled by placing circulating pipes in the lower reservoir. For frequent service the weir pattern is that usually adopted, in which

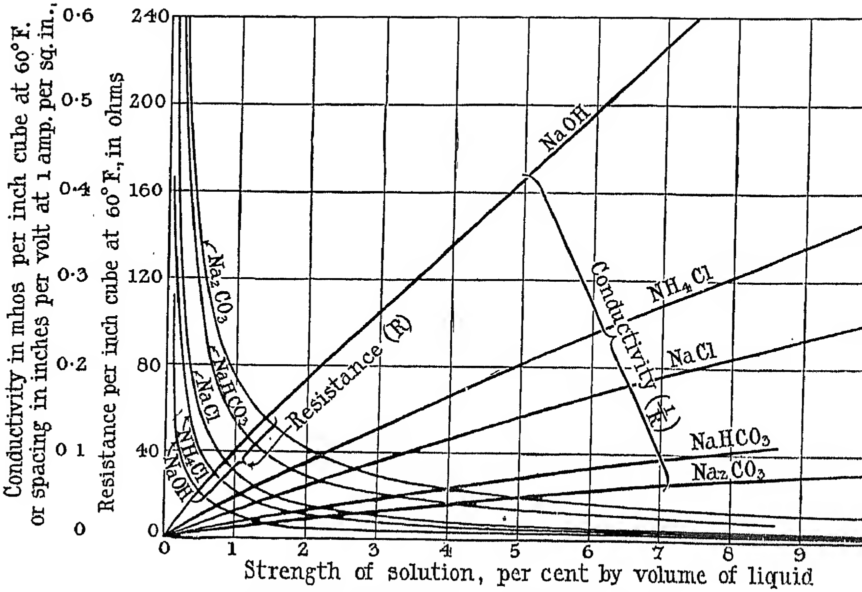



*Fig.* 67. Resistances and conductivities of electrolytes at various degrees of concentration.

the level of the liquid in the upper tank is regulated by means of an adjustable gate forming practically the whole of one side, as indicated in Fig. 179. This gate is directly operated by the controlling handle, which does not now have to deal with the pumping motor, the latter being kept constantly running. To accelerate the motor to any given speed, it is therefore only necessary to raise the weir to the position corresponding with that speed, whereupon the pump will fill the rheostat tank up to that level, speeding up the motor at a fixed safe rate.

This last type of liquid controller is much used for mine hoists and haulages, and in general for the control of the largest motors, requiring rapid as well as frequent operation. In some cases hoist motors require to be fully accelerated in ten or even seven seconds. The application of the liquid controller to mining work is further dealt with in Chap. XIX.

¶ ELECTROLYTES.—In most cases met with in practice the electrolyte consists of a weak solution of washing soda, which is a somewhat impure form of sodium carbonate. Other salts employed are bicarbonate of soda, common salt, sal ammoniac, and caustic soda. Particulars of the conductivity of electrolytes formed by these are given in the diagram in Fig. 67. There are two sets of curves in this, of which those resembling a hyperbola give the resistance in ohms per inch cube of the various solutions at normal temperature, according to their strength. The radiating lines give the reciprocal values of these, viz.

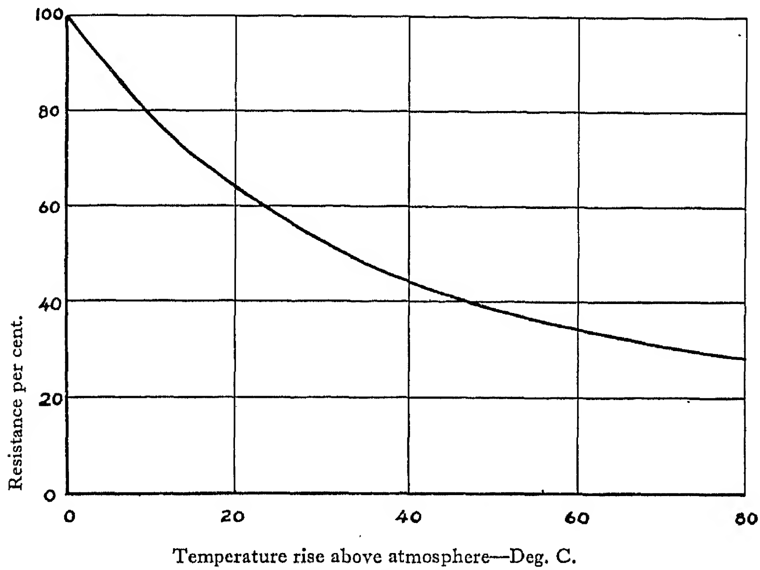



*Fig.* 68. Curve showing percentage reduction in resistance with rise of temperature of aqueous solutions.

the conductivity in mhos per inch cube; and they also express the spacing of the electrodes in inches per volt at a current density of one ampere per square inch.

Following the general rule for non-metallic resistors, liquids decrease in resistance with temperature. The curve given in Fig. 68, showing the rate at which the resistance falls off, is sufficiently correct for any water solution.

For use in situations where the electrolyte is exposed to temperatures below 0° C., it is of advantage to employ some salt which has a special affinity for water, and consequently solidifies at a temperature well below the usual freezing-point. Caustic soda and sodium nitrate are such salts, but the best is calcium chloride, the resistance/concentration curve of which corresponds closely with that of common salt. Its chief

drawback is its corrosive effect upon iron, which may, however, be obviated by adding a small amount of a soluble chromate to the electrolyte. A 13 per cent. solution of calcium chloride freezes at −6° C.

The addition of glycerine to an electrolyte also retards freezing. For example, a 14 per cent. solution of common salt in a 20 per cent. mixture of glycerine with water freezes at about −15° C. and has a resistivity of 5 ohms per inch cube.

¶ Design. The design of a liquid rheostat is chiefly a matter of ascertaining the maximum safe current that may be passed through a given area of the electrodes ; the permissible duration of the current, which is governed by the amount of energy that can be absorbed in a given time without causing overheating ; and the maximum safe voltage gradient through the electrolyte.

With regard to current density, conditions until recently have been somewhat chaotic, since various authorities have laid down widely different rules in this respect. For example, the maximum safe current that can be passed per square foot of electrode area has been variously estimated to be 30, 100, 144, and 400 amperes. At the present time most electrical pocket-books give a figure of one ampere per square inch, corresponding to the third of the above estimates ; but this, as well as the other figures quoted, is now known to be very much lower than is permissible in practice.

An investigation by the author,[1] published about five years ago, included tests made with both alternating and direct current, in which current densities were reached of over 11,000 amperes per sq. ft. with alternating and 5,760 amperes per sq. ft. with direct current, without causing any sign of break-down. Voltage gradients up to 2,400 volts per inch were also imposed with impunity. These tests effectively showed that the limitations originally observed were quite unwarranted. As a matter of fact, excessive caution with regard to current density was engendered by observations made upon the results of conducting high-tension current into and out of pure water by means of pipe electrodes, from which the lines of flow were radiating, causing a very large proportion of the total energy to be liberated at the surface of the electrode. A sudden and intense local evolution of steam was thus brought about, which was a sufficiently poor conductor to interrupt the current completely at frequent intervals. This state of things does not exist in commercial rheostats, in which the current flow is designed to be as nearly along parallel lines as possible.

During the above-mentioned tests a sufficiently good circulation of the electrolyte was promoted to prevent serious ebullition. In practice the production of heat would demand more liquid than could be contained in a rheostat of such compactness as to employ anything like the high current densities that were then attained. A density of about 3,000 amperes per sq. ft. is actually utilized in certain marine liquid

[1] See ‘ Some Notes on the Design of Liquid Rheostats ’, *Journal I.E.E.*, vol. 60, No. 306, Feb. 1922, p. 196.

regulators ; but it will be generally found that densities of the order of 1,000 are the most that will be required in practical work.

The second factor that requires determination is the heat capacity. This is generally expressed in H.P.-minutes, being the product of the average H.P. passed through the rheostat and the number of minutes which elapse before the temperature of the liquid is raised to a given value. The latter has been fixed at 50° C. (90° F.) by the British Engineering Standards Association.

Now almost exactly three-eighths of a pint of water is raised 50° C. by one H.P.-minute ; and this relation will enable the amount of liquid necessary for the absorption of a given amount of energy to be found. For very rough calculations it may be assumed that the energy in a liquid mass in H.P.-minutes is three times the volume of the latter in

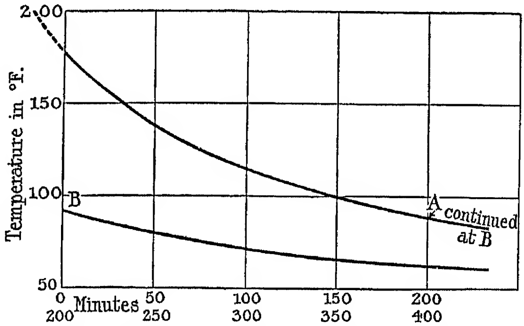



*Fig.* 69. Cooling curve obtained by experiment from rheostat in Fig. 63, by filling it with boiling water and allowing it to cool naturally.

pints ; this latter relation will actually give the amount of energy that will raise the temperature through 100° F. In the case of an actual rheostat the heat-absorbing power of the metal should also be taken into account, by adding its water equivalent to the figure representing the quantity of water. This may be simply carried out by weighing the amount of iron in pounds and adding one-tenth of the figure so obtained to the volume of the liquid in pints.

For example, in the case of the rheostat illustrated in Fig. 63, the amount of liquid was 30 pints, and the tank and electrodes weighed 70 lb. The water equivalent of the iron was therefore 7 pints, and the total amounted to 37 pints, giving a thermal capacity of $37 \times \frac{8}{3}$, or 99 H.P.-minutes.

Thus the heat-absorbing power is given, and the performance of a rheostat may be determined by comparing this with the energy given off by the starting or the control of a motor. For example, in the case of a starter, the energy liberated is half the total taken from the line during the whole starting period, the motor absorbing the other half. If a single start is made, or several in quick succession, followed by a

long interval during which the starter will have time to cool, the capaci of the latter will at once be given by simple arithmetic.

But if the duty required is periodic, and the intervals not long enou to permit a return to the original temperature or thereabouts, the ra of cooling during the intervals must be known. This can be carri out by plotting a curve such as that in Fig. 69, whereupon temperatu charts such as are shown in Fig. 70 may be compiled. In these t motor is supposed to be started every 16 minutes, the duration of t starting period being one minute. The approximately vertical cor ponents of the curves are obtained by the calculation just given ; wh those roughly at right angles to them are copied from the correspondi portion of the cooling curve in Fig. 69, at the temperature when cooli

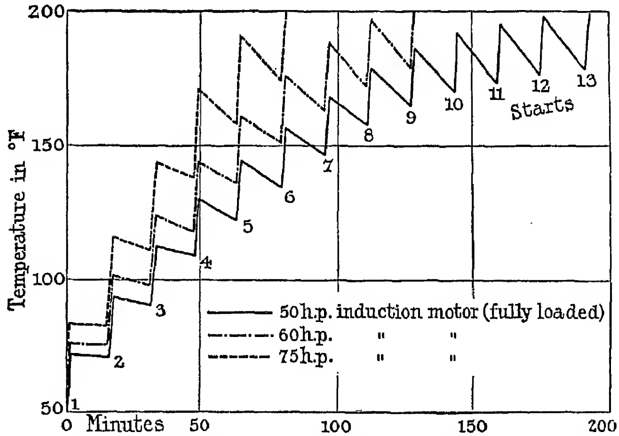



*Fig.* 70. Curves showing temperature fluctuations of rheostat in Fig. 63 when used with three capacities of motor.

begins in each case. These curves have been drawn for three capacit of induction motor, viz. 50, 60, and 75 H.P. respectively, supposed be fully loaded, and the diagram shows the rate at which the tempe ture of the liquid will rise, and therefore the number of starts that c be given before any prescribed temperature rise has been exceeded.

If a model of the starter is not in existence, and hence the cooli curve cannot be found by experiment, it can be constructed appro mately by erecting ordinates at 10 minute intervals, and making th diminish by a constant ratio $K$, which may be found from the followi equation :

$$K = 1 + \frac{0{\cdot}00234 \times \text{cooling surface in sq. in.}}{\text{volume of liquid in pints} + 0{\cdot}1 \text{ weight of iron in lb.}}$$

Liquid rheostats for controller or other duty may be calculated ir similar manner, including the provision of water circulation. It w be found that between 3 and 6 gallons of cooling water are requir

per H.P. dissipated per hour. The pressure of the supply should not exceed 50 lb. per sq. in.

*Rating.* The B.E.S.A. standard ratings are given in the following table:

TABLE 10. STANDARD RATINGS OF LIQUID RHEOSTATS

| *Standard Size. No.* | *H.P.-Minutes per 30 min. taken from Line.* | *Maximum Rotor Current. Amperes.* |
|---|---|---|
| 1 | 50 | 150 |
| 2 | 100 | 250 |
| 3 | 200 | 500 |
| 4 | 375 | 750 |
| 5 | 750 | 750 |
| 6 | 1,200 | 1,250 |
| 7 | 2,500 | 1,250 |

In this the first four are for either D.C. or A.C., while the remaining three are for A.C. only. It will be observed that the rating is not fixed according to the amount of energy to be absorbed by the starter, but according to the total energy taken from the line, the latter having already been shown to be double the former. Thus the starter will be capable of operating against conditions twice as severe as stated in the table. Hence a standard model, designed to carry out a given sequence of single starts, will be able to make twice as many as these, an amount of latitude that will cover a number of contingencies that may occur, such as, for example, the failing of the power supply for a short period immediately after starting has taken place.

The B.E.S.A. Regulations specify that the above conditions must be fulfilled for two successive half-hour periods without the temperature rise exceeding the 50° C. already laid down. Thus the rated size of a starter necessary for a given service is found as follows:

H.P.-minutes per 30 minutes =

$$\text{rated H.P. of motor} \times \text{starting time in min.} \times \frac{\text{starting torque}}{\text{full-load torque}} \times$$

number of starts per 30 min.

For example, to find the size of starter for a motor rated at 40 H.P., to start against 150 per cent. full-load torque once every 10 minutes, the starting period being $\frac{1}{2}$ min., the calculation is:

$$\frac{40}{2} \times 1{\cdot}5 \times 3 = 90 \text{ H.P.-minutes.}[1]$$

This would be met by a No. 2 size starter in the table.

[1] British Standard Specification, No. 140 (1923 edition).

# X

## CONTACTORS

IT is probably not very far from the truth to state that four-fifths the advances made by the electric drive during the last ten or fifte years have been due to the contactor and its allied apparatus. But spite of the variety of functions which the contactor successfully fulfi it is actually a remarkably simple piece of apparatus, constituting magnetically operated switch, and consisting essentially of a pair contacts which are closed by means of an electro-magnet. These cor ponents are easily distinguishable in the examples shown in the accor panying illustrations, which serve to show the simplicity of its desig Indeed, it is one of its greatest advantages that the elaborations intr duced into contactor equipment are almost confined to the stationa elements, such as the connexions.

The early history of the contactor is especially interesting, in that first designers had apparently no conception of the many advantag which it was destined to confer. It was adopted, to begin with, in ord to secure remote control, its circuit being closed by a pilot switch at distance from the contactor itself. Incidentally, it was also found provide a means for the making and breaking of heavy currents easi and safely, by the agency of a relatively light switch ; for large contac could thus be brought together or separated between the poles of a efficient magnetic blow-out. This obviated the labour required wh the operation had to be carried out directly by means of a large kni switch ; and also enabled the operator to remain at any desired distan from the separating contacts, and therefore in a safe and convenie position.

But the most valuable developments occurred when it was realiz that the pilot-switch principle rendered possible the automatic openir and closing of circuits. Since only a small exciting current had no to be dealt with, the operation of quite small contacts was sufficie to effect the control of large amounts of power. Various relays ther fore came into existence, designed to bring about the operation of cor tactors according to some prearranged plan. For example, the circu can be closed at stated times, or periods, as fixed by a clock mechanis or other time-element device ; or closing can be made to occur whe the current already flowing has fallen to a certain value. These tw types of relay give what are known as time-limit and current-lim control respectively, and by their agency automatic acceleration wa brought about in a much more efficient manner than before, renderin possible the speeding-up of a motor without risk to the machine itself while the time absorbed in the process is adjustable at the minimu value compatible with the safety of the whole scheme.

At the same time electrical and mechanical interlocks were devised which endowed the working of a contactor installation with a high degree of safety, regardless of errors on the part of the operator, or faults in the contactors themselves.

Employing these components, then, complete control equipments can be built up, the various parts being selected and arranged in order to achieve the performance of a great variety of functions. The design of contactor installations for completely regulating a complicated series of operations is an extremely interesting process, and one which abundantly repays expenditure of time and trouble by affording economy of labour, of working time, and of material.

¶ TYPES OF CONTACTOR.—There are various ways in which contactors may be classified. For example, they may be grouped according to the kind of current (i.e. direct or alternating) by which they are operated; according to their current-carrying capacity; the potential at which they are designed to work; the method in which the operating coil is connected in the circuit; the number and arrangement of poles or phases; whether single or double throw; whether normally open or normally closed; their individual function in the equipment, i.e. whether the unit is to serve for making or breaking the line connexions, for cutting out accelerating resistance, for dynamic braking, or other purposes; and so on. Practically all these methods of classification overlap, and a strictly categorical treatment is thus inadvisable. Nevertheless it is proposed to deal with the different types approximately in the above order.

¶ REQUIREMENTS IN DESIGN.—Before describing the various patterns in detail, it will be helpful to consider the qualities that are required of these magnet switches, if they are to fulfil satisfactorily the functions for which they have been brought into being.

In the first place, it must be remembered that the contactor has been largely introduced to protect the motor, and thus to increase the robustness and reliability of the electrical equipment. In order to effect this improvement, however, the fresh components must not be themselves wanting in the qualities desired, and they must therefore comply with the following conditions: (1) contactors must be certain in their action, never failing to close or to open the circuit effectively when their operating coils are appropriately connected or disconnected; (2) they must be capable of continuing to give reliable service for a sufficiently long period without requiring attention or repair; (3) their design must be such that they are not easily damaged or deranged under the usual working conditions; (4) when the replacement of any part is necessary, the design must be such as to enable this to be effected in a very short time, and by a single man.

The importance of the reliability of individual contactors is intensified by the multiplicity of units that usually go to make up a single control equipment; and it is obvious that if the whole is to give uninterrupted service, the performance of each component must be of a

very high order. The effect of failure in practice is frequently even more serious than would be gathered from what has been said, for it often happens that machines in a mill or factory are engaged in carrying out successive operations of a given process upon the same article, which passes through them consecutively. It is then possible for the stoppage of a single piece of apparatus to bring a whole section of a works to a standstill, and to cause an enormous loss when the derangement persists for more than a very few minutes. In a steelworks, for example, the unforeseen stoppage of an auxiliary motor attached to a blooming mill might involve a loss approximating to from £1 to £2 per minute.

Especial care will therefore have to be observed that excessive friction and residual magnetism are guarded against, these causing sticking in the open and closed positions respectively. Of the two effects, the latter is the more serious, since the failure to remove the driving force is usually more disastrous than the refusal to start, as may be realized when the conditions attending the control of a hoist or dock-gate are brought to mind.

Not only must the units perform well when new, but they must continue in substantially the same condition over a period of months or even years. This involves the provision of ample wearing surfaces at pivots and contacts, which must be designed to withstand at least a million operations even when slag or other finely divided grit finds its way from the atmosphere into all openings and crevices. The insulation of the arc-suppression devices must also be above suspicion.

Since replacements are unavoidable at some time or another, the design should facilitate the substitution of coils, contacts, pivots, and other parts that are at all subject to break-down, within a period of about a minute.

Finally, the whole apparatus must be able to withstand reasonably rough usage without any part becoming bent or fractured. There must be no delicate spring contacts, fine wires, or thin sheets of insulation, nor must so accurate a fit be required at any moving part that ordinary treatment is able to cause binding. The practice is to make all parts of a contactor heavy and strong, and all sliding or turning elements tending towards what is popularly known as a ' sloppy fit '. The contactors can then be relied upon to remain in a mechanically sound condition over long periods.

¶ Pull and Velocity Characteristics.—The duty that can be obtained from a given contactor, estimated in terms of the total current or power that it can connect or disconnect, depends primarily upon the strength of its electro-magnet at the significant points of the armature travel. To a less extent the speed of movement, both for opening and closing, influences its application. It is therefore of advantage to the designer that he should have accurate data regarding both characteristics, and this information will now be given in the shape of actual curves taken from representative examples.

Modern industrial contactors are almost entirely of the ' clapper '

type, in which an iron armature is pivoted in such a way that it can be attracted to the pole or poles of an electro-magnet. When the movement is complete the core, yoke, and armature form a closed magnetic circuit. In some cases the armature is pivoted about one of the magnetic poles, so that there is a single air-gap to interrupt this circuit, as shown at *A*, Fig. 71; and sometimes the pivot is located well below the lower pole-piece, as at *B*, there being then two air-gaps. It will be supposed that the coils are placed as indicated by the dotted lines, and that they constitute potential windings.

The relative force upon the armature when the coil is switched in varies widely according to whether the exciting current is direct or alternating. Let the former, as the simpler case, be considered first. Since the coil is connected directly across the voltage, the current flowing, and therefore the strength in ampere-turns, depends upon its resistance. This being constant under normal conditions, the magnetiz-

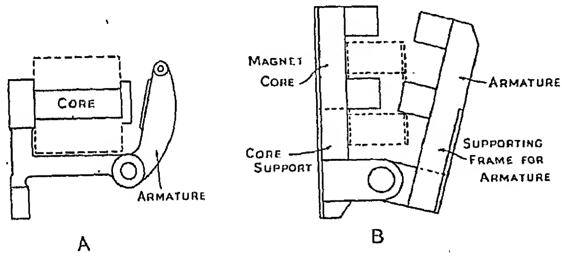



*Fig.* 71. Magnetic parts of typical D.C. and A.C. contactors.

ing force is also constant for all positions of the armature. When the latter is attracted to the poles, there is a minimum of reluctance in the iron circuit, and the flux (which can easily be calculated by the method used for the field of a dynamo) is great, usually approaching the saturation point. The pull, which is proportional to the square of the flux density, is great also. But when the armature is in the open position, the air-gap is interposed in the path of the flux, its high reluctance reducing the latter, and therefore also the pull, to a small fraction of their former values. Thus a D.C. magnet is weak in the open position, but strong when closed.

Conditions are very different with the A.C. magnet, for at a given voltage the current is now almost entirely dependent upon the reactance of the coil. When the armature is against the poles the reactance is a maximum, and the current therefore a minimum. The iron circuit has however its least reluctance, and the pull is thus quite great enough for practical purposes. But in the open position the greatly increased reluctance is accompanied by a greatly reduced reactance, and a consequent heavy rush of current occurs. Hence the pull is still comparatively strong.

These differing characteristics are shown by the curves in Fig. 72,

which record the variations in pull of two contactors having iron circuits of equal sectional area, one being a D.C. and the other an A.C. model. In each case the steady rated voltage was applied to the coil, and the pull on the armature was measured at different positions. The two curves, 1 and 3, give the pulls at the air-gap itself, and therefore afford a comparison between the strengths of the D.C. and A.C. magnets under exactly similar conditions. The great falling off in strength of the former is well shown, the pull when fully open being to that when closed only as 1 : 30. This may be contrasted with the much more even characteristic of the A.C. model, which has a variation of only

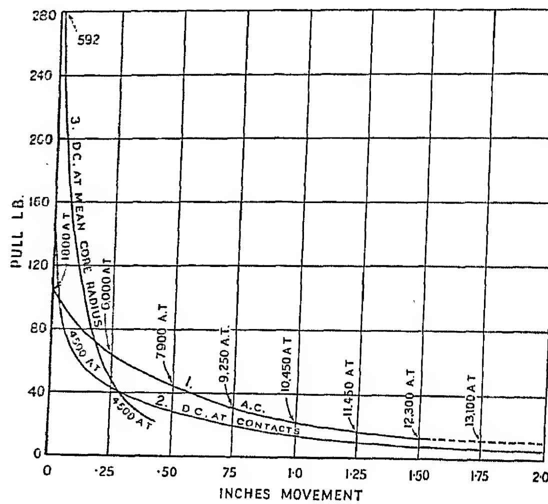



*Fig.* 72. Curves giving the pull of D.C. and A.C. contactor magnets of equal sectional area at different separations; pulls measured both at contacts and at cores.

1 : 2·1 over the same range, in this case amounting to a mean gap over both poles of 0·43 in. To complete the data, the relative currents taken by the two models at the various points are indicated by the numerical values of the ampere-turns marked against the curves.

The practical range in the A.C. case is even less than shown, for it would be impossible to make the contactor quiet at this excitation with the pull indicated acting against the closed armature. To avoid a disagreeable buzzing this force would have to be reduced to about 50 lb., and would thus be considerably less than at an air-gap of up to ¼ in.

These divergences have an important influence on design. Since the D.C. contactor can only be used over a small range of air-gap, it is always made in the form shown at *A* in Fig. 71, there being a single air-gap at the upper end of the armature. Owing to the limited pull in the open and semi-closed positions, D.C. models are not usually fitted

with more than a single pair of contacts, and these are conveniently mounted just above the armature, where the arc of movement is suitably magnified (usually about doubled) as compared with that at the air-gap. The A.C. magnet is, however, given a relatively much longer travel by being made as in *B*, the complete laminated magnet core and armature being mounted well above the pivot as shown. There is now sufficient power to operate more than one pair of contacts, and A.C. contactors are commonly designed to carry as many as three and sometimes four pairs without any change being necessary in the magnet. The moving contacts are mounted on one or both sides of the armature, being clamped to an insulated bar either fixed to the armature framework in some way, or forming an extension of the pivot. The radius of movement of the contacts is now about equal to the mean of the pole radii.

The two drawings in Fig. 71 are actually representations to scale of the D.C. and A.C. contactors from which the curves in Fig. 72 are taken, the core areas inside the coils being equal, and the ratings being 600 amps. and 300 amps. respectively. Curves 1 and 2 in Fig. 72 show the pressures produced at the contacts at various points of their travel, and indicate the greater amount of work performed by the A.C. model, enabling it to deal with four pairs of contacts, each of half the capacity of the single pair of the D.C. variant. An interesting comparison is also afforded of the inputs, for whereas the latter model required 4,500 ampere-turns over its whole range, the A.C. model took momentarily about 14,000 ampere-turns at the same contact separation as the other, and only 1,800 ampere-turns after closing, or a ratio of about 8 : 1. Since the smaller figure gives the final and continuous excitation, it will be seen that the A.C. contactor possesses a valuable inherent economy effect, rendering the continuous consumption well under half that of the D.C. coil. On the other hand, the initial current rush of the former upon switching in, rendered the more severe by the low power factor, is at times found inconveniently high for relays and potential transformers.

Turning now to speed of operation, a somewhat similar difference is exhibited by the two types, though from a somewhat different cause. The time taken for a flux to grow in a stationary iron circuit is entirely governed by the statical circuit characteristics. But as soon as motion begins with a D.C. magnet, a back E.M.F. is generated just as with a D.C. motor, and this then delays the rate of growth, causing the closing of the armature to be more gradual than would otherwise be the case. The phenomenon is not present with the A.C. magnet, which accordingly closes with far greater violence.

These effects are illustrated by the curves in Fig. 73, which give the results of speed tests on D.C. and A.C. contactors of the same capacity. They were made by connecting the stylus of a revolving disk apparatus [1] to the upper part of the moving contact in each case, so that the exact movement of the latter could be traced out. In the diagram the full

[1] See W. Wilson, ' Industrial Research, with Special Reference to Electrical Engineering Development ', *Journal I.E.E.*, Jan. 1924, p. 75, Fig. 4.

lines show the speed characteristics for both opening and closing of the D.C. model, while the dotted ascending curve shows the closing characteristic of the A.C. contactor upon the same scale.

It will first be observed that although an approximately equal interval elapses before either armature starts moving, the velocities after that point are widely different ; the contacts first touching in 0·082 sec. and 0·045 sec. in the D.C. and A.C. cases respectively. The apparent backward movement of the contacts after they have first touched is due to the ' roll ' of the moving contact horns, which recede from the fixed members as the point of contact shifts from the tip to its final position near the root. There is a brief recoil after the armature comes to rest, the contacts actually parting for an instant, and giving rise to a small arc when the current is flowing.

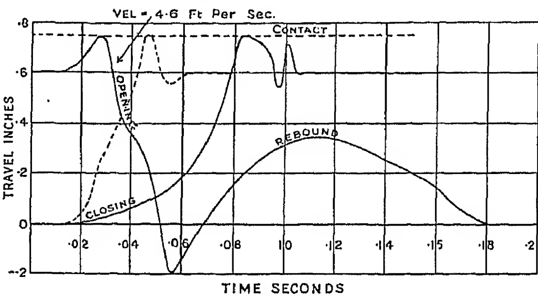
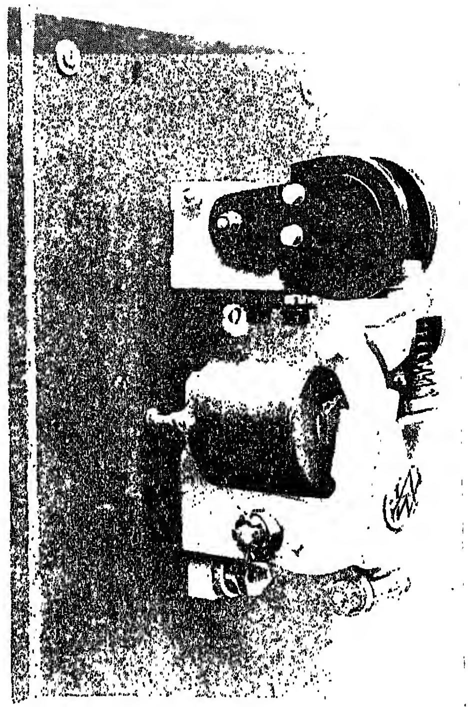



*Fig.* 73. Velocity curves of closing and opening of 150 ampere D.C. contactor, the former compared with closing of 150 ampere A.C. model (curve dotted).

The opening movement is shown by the descending curve, beginning with a reverse roll and ending in a quite considerable rebound. The armature is brought suddenly to rest by the ' off ' stop as the horizontal zero line is crossed, but the contact horn still continues moving, rotating about its own pivot and compressing its spring. It is then thrust forward again by the stored energy of the latter, and the momentum so developed, together with the recoil of the armature itself from its stop, causes the partial reclosing of the contacts shown in the diagram. The rebound of any contactor is much greater than is apparent to the eye, and bad specimens are even known to make a second contact. This is a serious fault in a contactor, and means should be taken to reduce the rebound as much as possible ; for if sufficient of the ionized gases remain in the gap between the two movements, it is not necessary for actual contact to take place to restart the arc.

¶ Direct Current Contactors.—D.C. contactors were originally made of the vertical solenoid and plunger pattern, and when designed for traction control their armatures are still arranged for vertical motion. Industrial models are now, however, of the general form shown in Fig. 71 A, a typical example being shown in Fig. 74. As regards material,

cast iron is most usual for small, and cast steel for larger patterns, the increased permeability and reduced weight of the latter metal outweighing its greaterc ost as the size increases. Pressed steel is, however, employed by some firms, and produces a neat design with a minimum of weight. Soft mild steel is always employed for the core, i.e. the part



*Allen West.*

*Fig.* 74. D.C. contactor in pressed steel, 150 amperes capacity.

of the iron circuit surrounded by the coil, in order to keep down the diameter of the latter to a minimum.

The various requirements enumerated in the introduction can be observed in these models. Of the parts subject to wear, the pivots and contacts are the most important, and these are made especially thick to secure long life. Hardened steel is usual for the former, and they must be held in place by some reliable means that can be disengaged in a few seconds. Split pins through the ends of the pivot outside the casting are a satisfactory method.

It is unfortunately the fact that the pivots cannot be relied upon to

carry the main current, and special flexible connexions are therefore necessary, leading from the contact to the stud that carries the current through the panel. These flexible conductors may consist either of copper braid, composed of fine wires plaited together, or of a number of flat thin strips or bands placed one on top of the other. Whichever pattern be adopted, it is important that the metal be hard and springy. If it is soft the connexions will soon fatigue and break where most bending occurs, i.e. close to the contact end. From the point of view of neatness, the necessity for these is to be regretted, though care in design can minimize the untidiness they introduce. An advantage of the pressed steel design of contactor is that the flexible strips can be accommodated out of sight in the hollow armature, as shown in Fig. 74.

The fixed contact is supported on a post projecting horizontally from the panel above the coil. In most designs, at any rate for moderate capacities, the contacts are of the 'horn' pattern, and the 'fixed' unit is attached rigidly to the post, the 'moving' contact, i.e. that upon the armature, being pivoted and pressed into engagement when the contactor is closed by means of a spring. The spring is thus brought to the front of the apparatus, and is very accessible for replacement. The reverse arrangement will, however, be met with occasionally.

Since the contact post has frequently to carry a magnetic blow-out, it is generally necessary to make it of non-magnetic material, in order to avoid short-circuiting any part of the flux.

The design of the magnetic circuit may be deduced from the principles that have been already stated. Since the air-gap must be minimized, the pivot is placed as close to the coil as possible. For the sake of compactness, the contact post is kept similarly close above the winding. The armature, bracket, and yoke may be proportioned on the assumption that 25 or 35 per cent. of the flux emanating from the core follows leakage paths and does not pass through the iron.

The shape of the air-gap is of some importance. It might at first sight be supposed that a greater pull would be obtained by the use of large diameter pole-faces; since these would reduce the reluctance of the gap in proportion to the increase in area. Some makers do enlarge the end of the core in this manner, up to about double its diameter, while others make the plain core project from the coil, which is then often held in place by a split pin passing through the pole.

In order to decide which of these practices to follow, it should be remembered that the magnetic pull is proportional to the square of the flux density multiplied by the area of the air-gap; or, more exactly,

$$P = \frac{B^2 A}{8\pi},$$

where $P$ = pull in dynes,
$B$ = flux density in lines per square centimetre,
and $A$ = area in square centimetres.

Thus it is an advantage to keep the flux density high, even if the area of the flux has to be restricted to accomplish this end. For

example, if the armature be closed, the magnetic flux flows entirely in iron, which is usually more than saturated. The quantity of flux is thus not altered appreciably by the proportions of the pole-faces; and the enlargement of the latter decreases the flux-density in proportion to the increase in area. Application of the above formula will show that the pull is weakened by the change.

The case is otherwise, however, when the armature is in the full-open position; for now the flux is almost entirely governed by the reluctance of the air-gap, and the iron part of the circuit is far below its saturation point. Enlargement of the pole-faces thus increases the

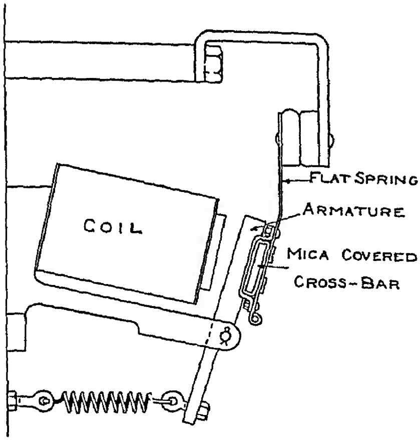


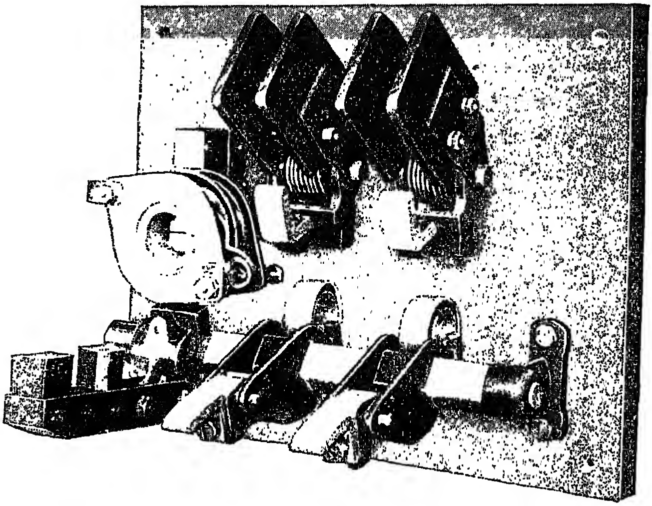

*Fig.* 75. Small 'normally closed' contactor, double-pole.

area of the gap without reducing its flux-density to any extent, and a stronger pull is the result.

Now there are two critical positions of the armature at which a definite strength of pull is needed. One is the full-open position, from which the weight of the armature has to be reliably lifted by the magnet when in its weakest condition; and the other occurs when the contacts are just touching, and the contact spring has to be compressed. With the latter there is a certain small amount of air-gap, and the case occupies an intermediate position between open and closed. In general, it will be found that modifying the pole-face does not affect this pull very strongly; but if the length of the gap is unusually short, or the spring strength great, a small diameter is advantageous. It must also be borne in mind that the enlarged pole-face reduces the length of the leakage path for the flux to the pivot. The correct diameter is therefore a matter that must be found for each design, and the simplest method is by experiment. For a given contactor, it was found by the author that a core-plate of one and a half times the core diameter gave

the best results, while with a larger model, having much stronger contact springs, the bare core diameter was appropriate. It is important that the armature is pulled right home when it has been attracted to the 'tips touching' position; and it is therefore the rule to make the pull somewhat stronger here than when the air-gap is a maximum. The momentum acquired by the armature during the first part of its movement is ignored both for designing and for testing purposes.

Instead of the magnet pulling the contacts together, the design may be inverted, the contacts then being normally closed, and being pulled



*General Electric Co., Ltd.*

*Fig.* 76. Typical model of an A.C. contactor.

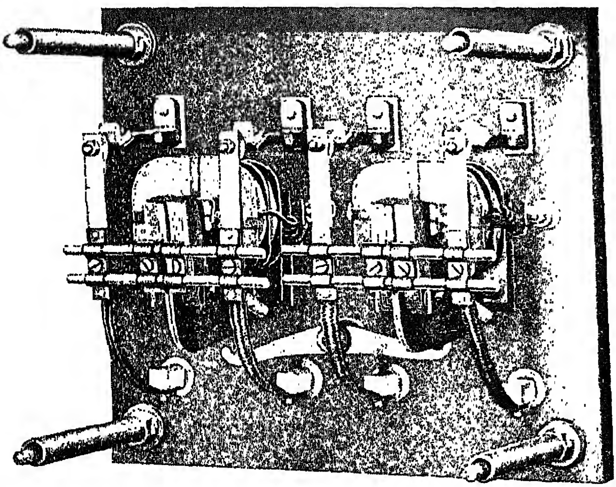
open by the flux. This type of contactor may be required for dynamic braking and for 'creeping', among other purposes. A small double-pole example is shown in Fig. 75.

¶ Alternating Current Contactors.—The A.C. pattern of contactor resembles that employed for D.C. in being usually of the 'clapper' type, but there are certain characteristic differences rendered necessary by the peculiarities of the alternating current. These may mostly be deduced from what has already been said.

First, the iron circuit consists as far as possible of thin laminations, No. 28 or 29 S.W.G. transformer iron being a usual material. This is clamped by bolts and rivets between or on either side of a stiffening framework of pressed or wrought steel, cast steel, or annealed cast iron, the object of course being to avoid the eddy currents that would be induced in solid metal, which would waste power and cause overheating.

Secondly, on account of the greater strength of the A.C. magnet at a wide separation of the poles, a much greater length of air-gap is employed. The pivot is located well below the lower air-gap, thus avoiding the problem of designing a laminated hinge; the moving contacts are given a comparatively short radius; and as many as four of these are operated by the one magnet.

As will be seen from the illustrations, the armature and contacts are usually clamped on an insulated rocker shaft. This may be of square rod covered with a $\frac{1}{16}$ in. layer of micanite; but there is no



*Metropolitan-Vickers Electrical Co., Ltd.*

*Fig.* 77. Two small two-pole A.C. contactors, capacity about 20 amperes, with moving contacts clamped to a pair of mica-covered round bars. The flexible connectors and shading rings should be noted, and also the seesaw interlock.

need for the insulation to extend through the armature clamp. Many makers combine one of the bearings of the shaft with the magnet frame; but in the author's opinion this is apt to complicate the latter without conferring any particular advantage. In the design shown in Fig. 76 the shaft is mounted in duplicate plain bearings, while the magnet frame is stamped out of ordinary angle-iron.

An alternative to the rocker shaft is sometimes adopted, especially for small models with only two phases. In these the armature is hinged on a bracket as with the D.C. pattern, and the contact arms are clamped on an insulated bar fixed to the front or back of the armature frame, as illustrated in Fig. 77. The construction of the armature and bearings is much simplified by this means, at the expense of a certain amount of lateral rigidity.

A plain magnet excited from an A.C. source would possess the great

disadvantage that the magnetic pull would entirely cease twice p
cycle, and would permit the armature to recede from the magnet by
small amount at each null point. The chief effect of this action woul
be the production of an intolerable buzzing noise whenever the arma
ture was closed, and the device known as a 'shading ring' is introduce
to secure silence. Rather more than half the core at the pole-face
surrounded by a ring forming a low-resistance secondary winding i
which currents are induced by transformer action with the contacto
coil, here functioning as the primary winding. The result is that th
flux in the portion of the core encircled by the ring is retarded in phas
its null points occurring when the rest of the core is exerting a definit
attraction, and vice versa. Thus there is never an interval during whic
there is no pull; and, since the pole-faces do not separate, the noise i
abolished. Another use of the shading ring to produce a two-phas

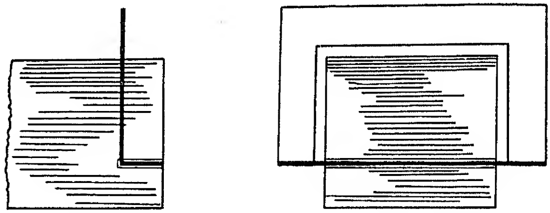



*Fig.* 78. Flat type of shading ring.

effect has already been described on p. 24, in connexion with smal
induction motors.

The principal care needed in designing the shading ring lies in pro-
portioning its resistance and cooling surface to the potential and powe
in its circuit. Now the voltage of a transformer secondary depends o
the ratio of the turns in the two windings. In this case the secondar
has only one turn (equivalent to half a turn, since it embraces onl
half the total flux), while the primary has many turns in a small model
and comparatively few in a large one. Thus the voltage in the ring i
low in a small and high in a large contactor. In the former case a com-
paratively thick ring is used, with well-made low-resistance joints
fitting closely round approximately two-thirds of the core. But with
larger units of, say, 300 or 600 amperes per phase such a ring would
pass far too much current. Not only would it overheat badly, probably
even becoming red hot, but the choking effect of the short-circuiting
winding would be very much overdone, and the contactor would be
noisy through the flux being largely prevented from going through the
ring at all. Consequently, for large contactors the ring circuit must
contain a sufficient amount of resistance to limit the current to a work-
ing value, and must possess sufficient cooling surface to keep the
temperature within safe limits.

These characteristics are obtained in two ways. The original method consists of taking the ring through the slot in the pole-face, and then back behind the coil, or even through the slate panel, where a small resistance element is included. A more recent method is illustrated in Fig. 78, whereby the whole ring is composed of resistance material to limit the current, and is made flat and thin to present sufficient cooling surface. It has the shape of a small hollow square, one limb of which fits into the narrow slot, while the rest is bent up at right angles, forming a compact and mechanical design.

A convenient method for arriving at the correct proportions of the ring is to complete the contactor except for this component, and to pass a long copper strip or wire through the ring slot. The coil is then excited, and by means of a sliding clip the legs of the strip are connected together and the point of contact moved until the best position for silence is obtained. Then this experimental ring will possess the required resistance and pass the required current, which can be measured by an ammeter. From these figures the watts dissipated in the form of heat can be calculated according to the equation

$$W = I^2R.$$

The final design can then be got out with the ascertained resistance, and with a cooling surface of about half a square inch to the watt. This experimental method incidentally affords a very convincing demonstration of the function and effect of the shading ring.

¶ Line and Accelerating Contactors.—The distinction between line and accelerating contactors is largely a matter of position in the diagram. For example, a series of plain shunt contactors might have their coils energized from an ordinary drum type master controller in such a way that the first ones to close connected the motor to the line, and the rest were then switched in by successive drum contacts to cut out the accelerating resistance in steps. The first units would then be line contactors, and the remainder accelerating units, and there would be no structural difference between the two models.

Instead of the hand-operated distributing switch, progressive contact might be effected by one actuated by a solenoid or motor, giving automatic time-limit acceleration, or current-limit relays might be employed. In all of these the contactors would not be modified in themselves, the only change being the addition of the relays to the scheme.

But current-limit acceleration can also be effected by means of specially designed contactors which do not require relays, such as series and shunt lock-out patterns, and these will be described later. The great object in deciding upon the method for automatic acceleration is to secure reliable and uniform closing of the contactors with the introduction of a minimum of complication. In particular, it is desirable to dispense with the making and breaking of contacts if this can be achieved without undue sacrifice of other desirable qualities. Since a current-limit relay possesses contacts that are to be operated by a

relatively small force, it suffers in this respect; but its action is positive and uniform, and it is therefore largely used in place of the less elaborate expedients that fulfil the same function. This device is described in Chap. XII.

¶ Series Lock-out Contactors.—The contactors that have so far been described both for D.C. and A.C. have been excited by potential or 'shunt' coils, connected across the full voltage of the circuit. Their action is simple, for they attract their armatures when the coils are energized, and release them when the coils are disconnected. A rather different type is, however, sometimes employed on D.C. systems, in which the coil is typically connected in series with the main current, and which remains open while the latter has values above the normal, closing when the current has fallen to this point. These contactors are

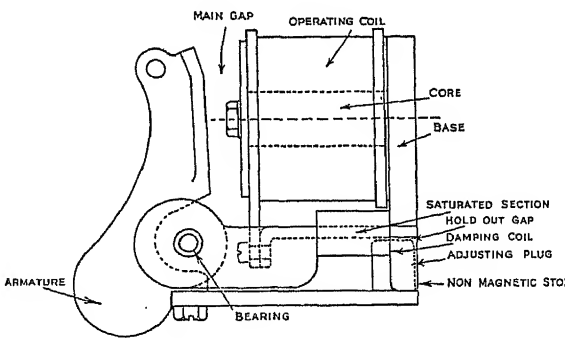



*Fig.* 79. Series 'lock-out' contactor by the Metropolitan-Vickers Co., Ltd.

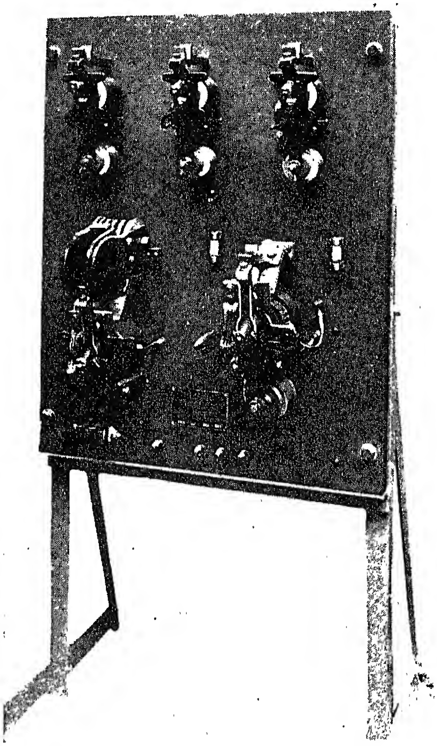
called 'hold-out' or 'lock-out' patterns, because the contacts are held out of engagement by overload values of the current.

The utility of this type arises from the fact that it does exactly what is required in accelerating a motor by cutting out starting resistance, without requiring a relay. Two varieties are illustrated herewith in Figs. 79 and 80, these being the single- and double-coil types respectively. The principle of each depends on the provision of duplicate paths for the flux, one of which is completely in iron, but includes a portion of restricted section that is saturated for currents above normal; and the other is of ample cross section but includes an air-gap. Of these the latter tends to oppose, and the former to bring about, the closing of the armature. For currents above normal the incomplete circuit has the advantage, but this is lost as the current falls. A thick copper ring is usually fitted round the restricted portion of the iron circuit, to delay the flux in this, when the coil is first switched on, until the current has reached its peak value, when it is able to hold out the armature.

The double-coil pattern is somewhat more definite, and therefore more certain in its action than the simpler model. The method of

connexion of the former is shown in Fig. 81; and the single-coil diagram may be deduced from this by omitting the lower coils. Another method is involved in the control diagram forming Fig. 141.

Series contactors can only be employed where partial speeds are not demanded, that is, where the motor is required to accelerate to full load



*Igranic Electric Co., Ltd.*

*Fig.* 80. Shunt-line contactor and four double-coil series lock-out accelerating contactors. Note the larger size of the final accelerating unit, and the shunt holding coil in addition to the series closing winding.

on every occasion. Generally, however, several running speeds are desired, such as 'creeping', half, and full speeds, and this gradation can readily be obtained when using shunt contactors by causing the master-controller to open the exciting circuit of any unit at which a pause in the acceleration is needed. Similarly, 'notching back' is not possible with the former type. A further drawback is that the contactors are liable to drop out if the load falls momentarily to zero, even at

full voltage. It will thus be seen that the application of series contactors is limited to plain automatic starting, where the load is not likely to approach the zero point. The addition of a shunt winding to the last series contactor of a set, as in Fig. 80, together with the auxiliary contacts for connecting it in circuit, is frequently utilized to deal with the last objection.

¶ COUNTER E.M.F. CONTACTORS.—Shunt-wound contactors are sometimes employed with their coils connected across the brushes of a D.C. motor, and they are thus excited by the back E.M.F. of the armature at any stage of its acceleration. By a simple adjustment of their magnetic circuit, such as the variation of the length of the air-gap, they can be

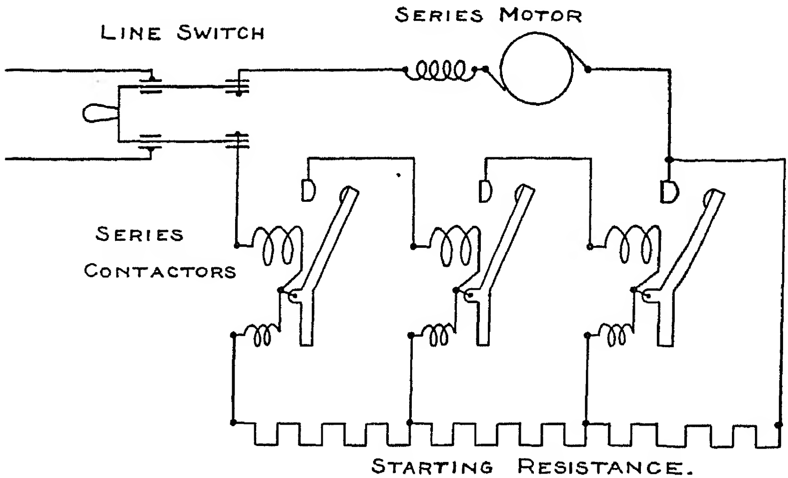



*Fig.* 81. Connexion diagram for double-coil contactors as shown in Fig. 80.

made to close at predetermined values of the E.M.F.; and by providing a series of such units, arranged to cut out successive stages of starting resistance, and adjusted to close at suitably graded values of the armature voltage, automatic acceleration is brought about without the use of additional circuits, coils, or relays. Such a scheme is ideal as regards simplicity.

Unfortunately there are two defects attending this principle which seriously limit its utility. In the first place, the voltage at which the contactor operates is altered considerably by the temperature of the coil; and since this normally changes to such an extent that the resistance rises, after it has been switched into service, by 20 or 25 per cent., the point at which the accelerating resistance is actually cut out is far from being definite. Secondly, fluctuations in the line voltage interfere with the scheme; for if this is low the acceleration is effected too slowly, while the last accelerating contactor may not close at all; while

too high a potential will speed up acceleration under conditions when the motor is already being overstressed by its unduly high speed.

The first of these defects is undoubtedly the more serious, for line voltages are nowadays maintained at a fair level of constancy, thanks to the exacting requirements of incandescent lamps. The coil difficulties would be overcome completely and simply if a low-resistance alloy with a negligible resistance/temperature variation were available for winding purposes. Such a metal is urgently required for many electrical purposes, and its development would confer a great benefit upon the industry.

In default of such a winding, the effect of temperature is countered in one design by a differential circuit arrangement somewhat akin to that of a series contactor. The effect of the rising temperature is felt equally in both circuits, leaving the difference, or the closing force, constant.

A simpler approximation is now, however, in order for a number of equipments, and is favoured by two present tendencies. One of these is to reduce the number of starting steps, rendering the scheme much less sensitive to slight differences in the voltage at which contact is made ; and the second is to use a coil composed of comparatively thick wire, connected permanently in series with a resistance having little or no resistance/temperature variation. By the absorption of a large proportion of the potential drop in such a resistance, the variation in the current through the coil circuit at various temperatures of the windings is considerably reduced, and the point of operation to a great extent stabilized. It is even practicable to use a series resistance with a negative resistance/temperature characteristic, so designed as to neutralize the positive variation of the coil. Such a characteristic is afforded by carbon, and to a much smaller extent by certain alloys, such as annealed manganin.

Quite large motors are now started with only a single step of resistance, especially when they possess a compound field. The use of the C.E.M.F. mode of acceleration should therefore increase in the near future.

¶ THE SHUNT LOCK-OUT CONTACTOR.—The principle of holding the armature open by an opposing flux, utilized in series lock-out contactors, is also employed with shunt models for governing the acceleration of a motor without the use of relays. In this case the shunt coils are all excited at the beginning of the operation, but the armatures are prevented from closing by the counter-attraction of a series coil through which the motor current passes. As soon as the latter has fallen to such a point that the shunt coil is able to overcome the pull of the series coil the contactor closes.

This is again a comparatively simple method of solving the problem, there being no additional moving parts or contacts for controlling the acceleration. It however suffers from the same objections as the previous type, in that the point of closing is seriously modified by the

inconstant strength of the shunt coil. The same general remarks therefore apply, and much the same remedies are available.

The example in Fig. 82 shows another method of minimizing the defect. There the lower coil, instead of directly opposing the upper, compresses a spring that is several times as strong as the latter in the open position. When the pull of the series coil ceases to be strong enough to compress the spring, it permits the armature to move forward, coming more under the influence of the shunt coil, which definitely completes the movement.

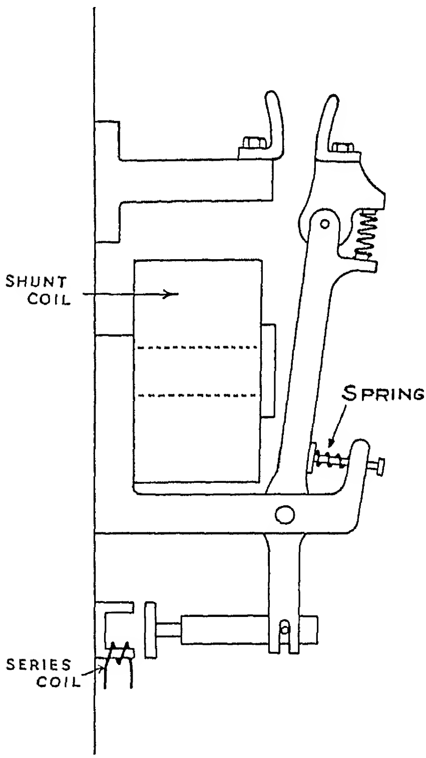
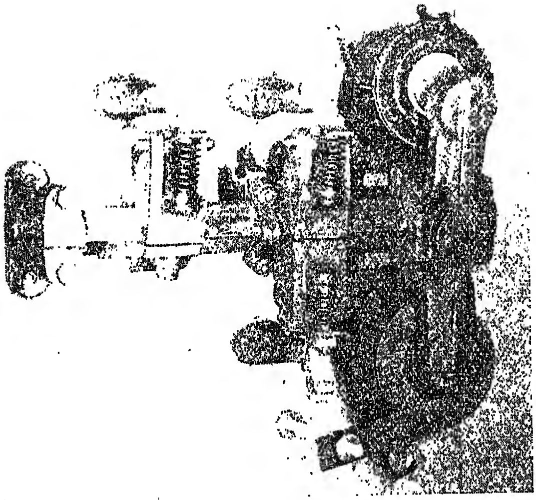



*Fig.* 82. Diagram of shunt lock-out contactor, showing balancing spring.

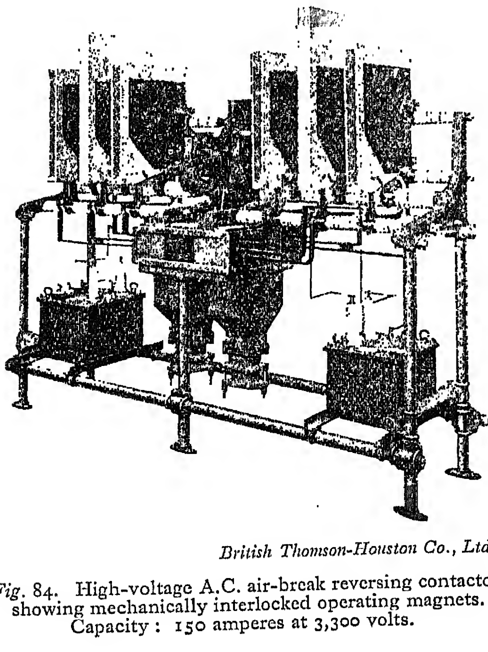
¶ DOUBLE-POLE AND DOUBLE-THROW D.C. CONTACTORS.—When automatic switching is required upon two poles or in two approximately equal D.C. circuits at the same time, it is the usual practice to carry it out by means of two distinct single-pole contactors, in preference to employing a double-pole unit. This does not introduce as much additional duplication as might be imagined, for many parts, such as the contacts, are doubled in any event, while the remainder, such as the coil and the magnetic circuit, would need to be of just twice the size for the double duty, owing to the weakness of the D.C. magnet in the open position. Moreover, the use of nothing but single-pole units in an installation maintains a convenient uniformity in the constituents, simplifying the design and reducing the number of spares, as well as of components in the Factory Stores.

There are, however, minor advantages in the double-pole principle, one of which is that both poles are bound to act in unison ; but it is not customary to depart from the simpler design unless the further complication of a reverse contact is required in addition. Such a double-throw pattern is of great use for dynamic braking, and the example in Fig. 83 provides for connecting one end of the motor armature to the braking resistance when the contactor is in the open position,



*Metropolitan-Vickers Electrical Co., Ltd.*

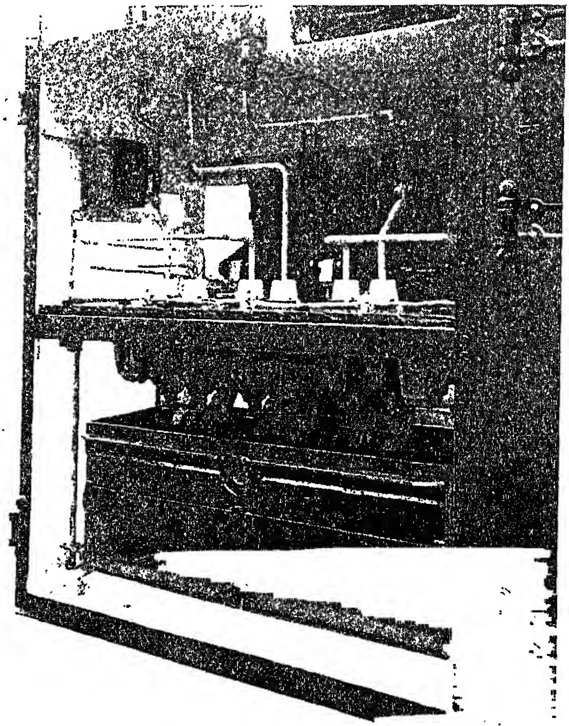
*Fig.* 83. Double-pole double-throw D.C. contactor for dynamic braking.



*British Thomson-Houston Co., Ltd.*

*Fig.* 84. High-voltage A.C. air-break reversing contactor, showing mechanically interlocked operating magnets. Capacity: 150 amperes at 3,300 volts.

and the closing of both poles for running in one direction when the shunt coil is energized. There is also a thick wire coil in series with the brake resistance, for pulling the back contacts firmly into engagement as long as any braking current flows. Thus not only is an efficient contact made for this current, but the contactor armature is forcibly



*General Electric Co., Ltd.*

*Fig.* 85. Oil-immersed high-tension A.C. contactor, rated at 300 amperes and 3,300 volts. Note double-break contactor.

prevented from closing, even if the shunt coil is energized, as long as the motor is rotating and driving current through the brake circuit. The design also provides for the direct interlocking of the line contacts and those for the dynamic brake. Further information is given on this head in Chap. XIII.

¶ High-tension Contactors.—The types of contactor that have hitherto been described are adapted for voltages of not more than 600; and the modifications now remain to be described that are necessary to enable high potentials up to about 6,600 volts to be dealt with. These in general follow ordinary switch practice, in that air-break contacts

having a long separation are available for units up to 5,000 volts ; while oil-immersed patterns do duty for the higher voltages.

An example of air-break contactor is shown in Fig. 84. This is a three-phase unit, and the usual form of operating magnet is shown mechanically connected with light moving contacts by means of long insulated rods. The horns are unusually large, and both sets are now made stationary, the moving contacts being electrically connected to the front horns by means of flexible connexions. Thus the arc is first struck at the separating contacts themselves, and is transferred to the front horn by the moving contact as it passes. By this means the moving system is kept light. These contactors are rated at from 50 to 500 amperes, at voltages up to 3,300. They are particularly suitable for mine hoist applications, being used in conjunction with a liquid controller for the rotor circuits of high-voltage induction motors.

A good example of a high-voltage heavy-duty D.C. contactor is shown in Fig. 91 in the next chapter. This model embodies the 'unit' principle, whereby two similar components are employed in series, forming in this instance a double-break combination rated at 2,000 amperes and 3,000 volts. The vertical coil design has the advantage that the main circuits and the operating coils can be well separated electrically, the only connexion being a mechanical one, effected by means of a rod of specially selected wood.

Oil immersion can be effected in two ways—the standard low-tension type of contactor may be completely submerged in an oil tank, or a special design can be adopted, in which the contacts only are immersed, and the magnets are situated above the oil, operating the former by means of vertical rods. The first pattern is suitable for comparatively low voltages, e.g. not above 2,300, and for infrequent duty, such as the occasional starting of motors. The second type is suitable for the more severe duty, being employed in the usual single-break form up to 4,000 volts, and with two breaks in series from this voltage up to 6,600. Fifteen breaks per hour can be safely effected by the model illustrated in Fig. 85, which is shown with the oil tank lowered, and is rated at 300 amps.

# XI

## CONTACTOR COILS, CONTACTS, AND OTHER DETAILS

THE general design of contactors having been dealt with, consideration will now be given to that of the electrical and mechanical details.

¶ OPERATING COILS.—The operating coil of a shunt contactor is its most important feature, for it absorbs as a rule more than half the total cost and is the part that is most liable to give trouble if its design is carelessly carried out. It is the power-consuming and force-producing part of the apparatus, and the design of the whole is based upon its capabilities. If therefore the efficiency of this component falls short of what is practicable, the good qualities of the complete contactor will inevitably suffer.

It must first be made clear that the electrical design of the winding differs radically according to whether the exciting current is direct or alternating. A direct current is limited in magnitude by the resistance of the circuit only. If the length and therefore the resistance of each turn were exactly equal, then the 'strength' of the coil for a given potential would be constant whatever the number of turns; for the current would be inversely proportional to the latter, and therefore the strength in ampere-turns, the product of these two, remains the same. This can easily be realized by taking trial values of the voltage, number of turns, and resistance per turn, and calculating the strength for each case.

Thus it is established that although the length of the turns varies somewhat from inside to outside of the coil, the strength for a given size of wire is not altered to any great extent by varying the number of turns. Since the outer turns as a matter of fact introduce more resistance than the inner ones, and the strength is hence reduced to a slight extent by adding more wire, the advantage actually lies with the smaller winding. The rule therefore is that for coils of different strengths, at a given potential difference, different sizes of wire must be used.

It can well be imagined, however, that the economy of wire by the employment of small coils is rendered impracticable by the overheating that would result. Since the energy turned into heat is represented by $EI$ watts, that is, the product of the voltage, which is constant, and the current, the energy absorbed and the heat produced vary with the current. Thus the production of heat is reduced by increasing the size of the coil. Again, the dissipation of heat is proportional to the cooling surface of the coil. For contactors the maximum temperature rise usually permitted, namely 40° C., is attained when a coil absorbs about one watt per sq. in. of curved surface. Now the latter is equal to the circumference multiplied by the length, or $\pi Dl$, and consequently varies with the diameter and therefore the number of turns. To sum

up, increasing the amount of wire on a coil does not alter the strength to a great extent, but reduces the working temperature. Taking all circumstances into consideration, the coil that gives the maximum economy is produced by making the overall length and diameter each about equal to three times the diameter of the core upon which the wire is wound.

The size of wire may be arrived at by a trial calculation from first principles. A size of wire is assumed, the diameter over the insulation is ascertained, and the number of turns per layer, and the number of layers are calculated from the coil dimensions as given above. These are multiplied together to give the total turns, and this is then multiplied by the resistance per mean turn, giving the total resistance. The current, strength in ampere-turns, watts consumption, and approximate temperature rise are then all easily found. If the result is not suitable, it will indicate the direction in which a further attempt may be made.

Instead of carrying out the above calculation repeatedly until a final satisfactory result is obtained, the following simple formula may be used, which will give the appropriate size of wire correct to one gauge, and will thus save much preliminary work:

$$\text{bare diameter} = \sqrt{\frac{1{\cdot}25\, NI\,(D+d)}{E}};$$

where $NI$ represent the ampere-turns required, $D$ is the outside diameter of the coil, $d$ is that of the core, and $E$ is the voltage. The result as given by this formula will require checking by direct calculation, using the exact particulars of the actual type of covering to be employed. In some cases it is found advisable to employ two consecutive gauges of wire on the one bobbin, to get results intermediate between those afforded by coils wound entirely of one or other of the gauges.

After a coil has been designed for a given contactor, to work at a given potential, windings for use at other voltages may be found by remembering that since all the coils have the same cooling surface, the sectional area of the wire to produce equal heating will be inversely proportional to the voltage, and therefore the wire diameter will be inversely as the square root of the voltage. Thus, if a given contactor is wound with wire of 0·024 in. diameter for 115 volts, a diameter of 0·012 in. will be appropriate for 460 volts. It is of course usually impossible to satisfy this relationship exactly in practice, and the nearest available wire gauge to that calculated, or a combination of the two nearest gauges on either side of that calculated, has to suffice.

Conditions are quite different when the power is alternating, for now the magnitude of the current depends almost entirely upon the reactance, the resistance being practically negligible. Since the reactance is proportional to the square of the number of turns, the current is inversely proportional to this, and the strength in ampere-turns is

inversely proportional to the number of turns. This may be summarized as follows :

$$I \propto \frac{1}{X}, \text{ where } X \text{ represents the reactance,}$$
$$X \propto N^2,$$
$$I \propto \frac{1}{N^2};$$
$$\therefore NI \propto \frac{N}{N^2} \propto \frac{1}{N}.$$

Thus it is established that the strength is actually doubled by halving the number of turns. The length of wire that can be used is strictly limited by this relation, and there is not the same elasticity in this respect as with the D.C. coil.

If it be supposed that a coil suitable for one voltage has been arrived at by trial or otherwise for a given voltage and periodicity, windings for other conditions may be easily obtained by remembering that the number of turns is proportional to the potential when the frequency is constant, and is proportional to the frequency when the voltage is constant. Both of these relationships can be easily verified from the data that have already been given. It will be found in practice that the space occupied by the windings is much less and the permissible size of the wire is much greater than in the case of the D.C. coil.

Again, the reactance of a coil is proportional to the area it encloses, and therefore the windings of A.C. contactors must contain fewer and fewer turns as their size increases. In order to produce the required coil strength the exciting current must increase accordingly, and the excitation of these large contactors frequently becomes an awkward problem, especially as it may have to be controlled by comparatively small relay contacts, and also as the initial current when the armature is in the open position is from six to ten times its final value.

According to specification (see B.S.S. 129 or 155), it is necessary that contactors shall give their rated performance with the coil at its working temperature, and at 80 per cent. of the rated voltage in the case of D.C. and 85 per cent. of this in the case of A.C. models. These conditions must therefore be allowed for. The rise of temperature of the windings, if insulated with silk, cotton, paper, or similar material, and subsequently impregnated, and if left in circuit continuously under rated conditions, must not exceed 40° C. ; and the same is stipulated for enamelled wire, even if not impregnated. This rule holds good for release and blow-out, as well as operating coils. But if the two former are insulated with refractory material such as asbestos or mica, or if the coils are bare, a temperature rise of 100° C. is permitted. Similarly an operating coil may have a rise of as much as 90° C. if it is manufactured by suitable special processes ; but this is only allowable when a replica model has been guaranteed to have satisfactorily withstood these conditions for at least twelve months.

A semi-practical method for accurately designing a range of coils for a given contactor, which avoids the more serious uncertainties and labour of calculation and at the same time makes allowance for all necessary practical conditions, is to fit a trial coil of any convenient gauge in the case of a D.C. model, or number of turns in that of an A.C. unit, and test the contactor with this coil, the applied voltage being varied until the required performance is given. In the former case the E.M.F., and in the latter case the E.M.F. or periodicity or both, will be adjusted to give the specified final rise of temperature, with the coil left continuously in circuit. This will then be the maximum rated voltage, at the frequency employed if the current be alternating, for that coil, and the contactor must give its specified performance as regards pulling in and spring pressure at 80 per cent. of this figure for D.C. coils and 85 per cent. for A.C. If this condition is fulfilled, the correct windings for the whole range of standard voltages are found from the rating of this one by the simple relations already given.

The varieties of wire of which contactor coils are wound are alike in that they are all composed of pure copper ; but there are many types of insulation in use whereby adjacent turns are insulated from one another. In all of these the endeavour is made to provide a good and reliable insulation, able to stand the wear and tear of high-speed winding, and perhaps unwinding and rewinding in addition. The cost must be as low as possible, and the proportion of the total volume occupied by the copper, or the 'space factor', must be high. These qualifications are possessed by the various modes of insulation in differing degrees, and for this reason no single type is better than its rivals for every purpose.

To begin with, bare wire is sometimes used, neighbouring turns being separated by a thread of silk or cotton which is wound on at the same time as the wire. A thickness of paper is wrapped round each layer as it is completed, insulating it from the wire to be wound over it. This type of winding is very cheaply carried out by means of comparatively simple machinery, and it has a good space factor ; but unless it is carried out conscientiously the separating thread is apt to get out of place and permit the wires to come together.

The oldest method of ensuring separation is to cover the wire completely with silk or cotton, which is wound round it in much the same way as the wire itself is wound round the core. Either one or two layers may be used, the approximate increase in the wire diameter being indicated in the accompanying table.

Single-covered wires not only afford a thinner insulation, but they are much less robust than the double covering. They should therefore only be employed when the potential differences are not great, where requirements as regards space factor are exacting, and where great care is to be taken in the winding operation.

As will be seen from the table, cotton absorbs about three times the space that silk does, and, except for large wires, the loss of space may be a serious matter. This material is an inferior insulating medium to

silk, but has the advantage of a lower cost, as indicated in the table. After-treatment in the shape of dipping or impregnating is much more frequently carried out with cotton than with silk coverings.

TABLE 11. GROSS THICKNESS OF INSULATING COVERINGS FOR COPPER WIRE IN MILS

| *Size of Wire.* | *Silk.* | | *Cotton.* | | |
|---|---|---|---|---|---|
| *S.W.G.* | *Single.* | *Double.* | *Single.* | *Double.* | *Enamel.* |
| 45 | 1·2 | 2·2 | — | — | 0·35 |
| 40 | 1·3 | 2·5 | 4·5 | 6 | 0·7 |
| 35 | 1·3 | 2·5 | 4·5 | 6 | 1 |
| 30 | 1·3 | 2·5 | 5·5 | 7 | 1·2 |
| 25 | 1·5 | 3 | 5·5 | 7 | 1·8 |
| 20 | 2 | 3 | 6 | 7 | 2·5 |
| 15 | — | — | 7·5 | 10·5 | 3·3 |
| 10 | — | — | 8 | 10·5 | 3·5 |
| Relative cost for No. 30 S.W.G. per lb. . | 73·5 | 100 | 65·2 | 80·6 | 37·7 |

The above figures represent twice the radial depths of the insulation in each case. It is assumed that ordinary cotton is employed for the single covering, and specially fine cotton for the double.

A third material has come largely into use recently, having the degree of insulation and space factor of silk with at most the cost of cotton. This is enamel, applied as a coating of appropriate thickness by the passage of the wire at a suitable speed through a pot of the liquid insulation, which is subsequently baked. At the present time a strong prejudice against it is being dissipated, and its use is consequently increasing. This progress is justified by the great advances that have been lately made in its manufacture.

Regarding the elasticity and durability of the coating, very much depends upon the baking process ; and since this can be followed with the greater certainty by the observation of colour changes, the purple varieties are somewhat more likely to be correctly formed than the full black, and should be given preference. As a matter of fact, the only important defect of enamelled wire is due to the wire itself, which has occasional very small splintery projections on its surface as a result of the drawing-out process. These are successfully covered by silk or cotton, but may project through the enamel, forming microscopic bare spots. In practice it is found that the chances of two such spots on adjacent turns coming together are so remote that the possibility may be completely disregarded for most purposes. The consequences would only be serious in the case of A.C. coils, where a short-circuited turn would function as a low-resistance transformer secondary, and would attain a high temperature. For this reason it is wise to employ a thickness of rice paper between layers when the coil is to be used on an alternating circuit.

A somewhat thicker coating is sometimes specified for special pur-

poses; while in America a combined covering of enamel and single silk is used for some A.C. coils. The table will serve to bring out the great advantage gained by an enamel covering for the smaller wires, through the possibility of obtaining a reliable coating of low thickness appropriate for the differences of potential to be encountered by them.

Enamel has the advantage of withstanding safely a much higher temperature than either silk or cotton. Except for the proviso just made with regard to alternating currents, it may be freely used in place of the other coverings.

With regard to the support for the wire, coils may be wound on bobbins, generally composed of split metal tubes with end flanges of insulating fibrous material; they may be wound on a former, or collapsible bobbin, the finished coil being taped before the former is

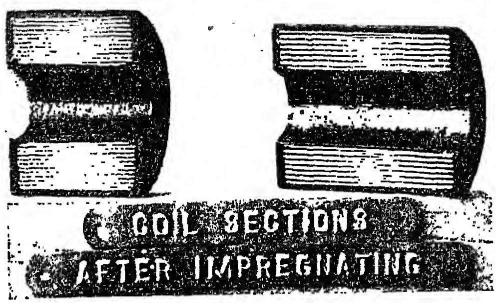



*Fig.* 86. Section of solid wound 'Leesona' coil.

removed; or they may be solid wound on a special machine, not requiring either bobbins or former.

The chief difficulty in using a bobbin is met with in connexion with the prevention of eddy currents. If any part can conduct a circulating current parallel with the winding of the coil, it will function as a short-circuited transformer secondary. In the case of D.C. contactors this effect will only be encountered when the coil is being switched on or off, and it will merely retard to a very slight extent the closing or opening of the armature. But when the coil carries an alternating current, heavy circulating currents will flow constantly, which will waste power and cause serious overheating of the part in question. Hence all such parts are made of non-conducting material, or are slit to prevent eddy currents from flowing.

Former coils are not used to the same extent with contactors as with dynamos, owing to the necessity of maintaining a regular and accurate shape. When the bobbin is omitted the wires are generally held together by a binding of cotton which is wound on at the same time as the wire itself. An example of this method is shown in Fig. 86, representing a section of a coil wound on a 'Leesona' automatic

machine. The wire has a single thin coating of cotton, and a cotton thread is zigzagged over the layer that is being wound. This not only holds the wire in place, but forms a tapered layer of insulation which increases in thickness with the voltage between the wires as the distance from the 'closed' end increases. After the wire has all been applied, the coil is finished off with an even winding of the cotton thread, and the whole is then made solid by impregnation. The partly wound coil is shown in Fig. 87.

Most coils, however they are wound, are improved by being impregnated with suitable varnish. When silk or cotton is used as a covering, the presence of damp can impair the insulation to a certain extent. Even if the materials are thoroughly dry to begin with, unless a completely air-tight and moisture-proof surface is formed all round the exterior, damp will be introduced by the 'breathing' of the air enclosed in the free spaces between the wires, brought about by changes in the temperature of the coil and in the atmospheric pressure. To remedy this the dry coils are placed in a container which is first rendered vacuous. When as much of the air is removed as possible, hot impregnating compound is run in and forced into the interstices under high pressure. Impregnation is not needed to the same extent with enamelled wire, and it is in any case difficult, since most varnishes exercise a solvent effect on the enamel.

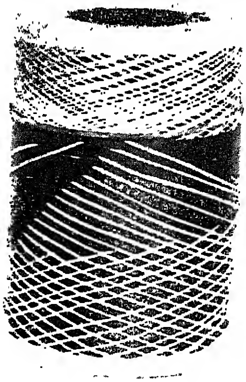


*Fig.* 87. Partly wound 'Leesona' coil, showing cotton over-winding.

The end connexions are best taken to copper lugs fixed to the outside of the coil. This may be done by bending them at right angles to form a foot, over which is wound the layer of string employed to finish off and protect the coil. Flexible wire 'tails' are also used, but are less robust.

Winding is accomplished in several different types of machine. The simplest is the ordinary winding lathe, in which the bobbin is rotated by belt or motor at a speed usually regulated by a pedal, while the operator guides the wire by hand. At the other end of the scale are the fully automatic machines, such as that responsible for the coil in the last two figures, several of which can be tended by the one operator. Which type is employed depends upon the volume of work being handled, and upon whether a small or large variety of coils is to be dealt with, for the value of an automatic machine is much discounted if frequent setting-up has to be carried out relatively to the amount of work done at one setting.

¶ CONTACTS.—The closing of the contacts is the work for which the contactor is designed, and these therefore deserve a certain amount of

consideration. The object that should be kept in view when designing them is to provide a path for the current which shall possess adequate conductivity, which shall require a minimum amount of power to close it, and which shall remain in good condition for the maximum length of time.

For models up to 1,000 amperes the horn pattern of contact is employed, shown in a number of the accompanying figures. It is usual to make both contacts of similar shape, and to pivot one of them so that they first meet at their tips, and the point of contact then 'rolls' until the current finally passes through the root of the horns. By this means the final conducting surfaces are kept remote from the arc formed upon breaking circuit, and the contact resistance is kept low. The motion of the one contact with respect to the other is in reality partly rolling and partly rubbing, and the degree to which each is present has an important bearing on the performance of the contactor.

Now the usual contacts are approximately an arc of a circle in shape, and on the assumption that there is no sliding the action of the moving member is that of one circle rolling upon another. The contact pivot forms a point attached to the rolling circle, which would trace out a cycloidal curve known as a hypotrochoid. This may be easily drawn out on paper by means of an outline of the moving circle or contact drawn on tracing cloth. The curve would then show the path through which the pivot would have to travel if pure rolling were to take place.

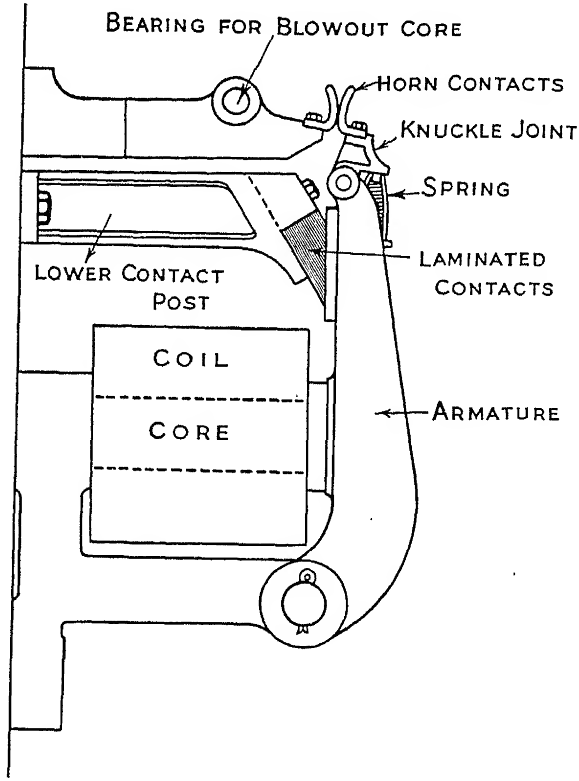
It is evident, however, that the contact pivot is compelled to move with the upper end of the armature, that is, in an arc of a circle described about the armature pivot as centre. The condition for minimum sliding is thus that the two paths must be as nearly coincident as possible.

It is found in practice that the amount of friction present when minimum sliding is secured is sufficient to keep the contact surfaces in good condition. More than this unduly increases the closing force required. If excessive sliding is permitted, closing may be arrested when the contacts are not brought fully into engagement, and the spring may thus not be fully compressed. The junction will then be an inefficient one, having too high a resistance, and sufficient heat may be developed to weld the contacts together. When the design is being got out, therefore, the construction indicated above should be made on the drawing, and the inclination of the contacts to the horizontal, the position of the pivot, and the curvature of the contact face varied until the 'rolling' curve and the actual movement of the pivot are in close agreement. It will be found that minimum rubbing takes place when the armature pivot and the knuckle-joint pivot at its mid-contact position lie on the tangent to the contacts drawn through the point where they touch.

The principle of 'line' contact employed with these horns may be novel to some readers, who may consider the necessarily small contact area to be inefficient. The reverse is, however, the case, for whereas flat surfaces usually touch at a few projecting points only, the curved

faces of these horns meet along a complete strip, the width of which is roughly proportional to the pressure brought to bear on them. This has already been demonstrated in Fig. 15.

Laminated contacts are generally employed when the normal current carried exceeds about 1,500 amperes, especially with D.C. contactors,




*General Electric Co., Ltd.*

*Fig.* 88. 2,500-ampere contactor, with double laminated contacts.

the pull curve of which (see Fig. 72) has a high peak value just where needed to compress the laminations. They consist of bunches of hard copper strips clamped in such a way as to present an inclined face to the flat contacts opposed to them, as shown in Fig. 88, and also in the two lower units of Fig. 80. They differ from the corresponding parts of air circuit-breakers in making and breaking contact at only one end of the laminations, since the force required, and therefore the magnet strength, would have to be doubled if both were engaged. The problem is thus introduced of leading the current into the laminations

at the end where they are clamped without involving an excessive resistance loss through requiring it to penetrate the numerous surfaces of the laminations, which probably make only indifferent contact with one another. In the example shown in Fig. 88 the pile of laminations have been given a wedge section towards the 'butt' end, and the inclined faces are forced by the set-screws into wedge-shaped slots, thus bringing the two edges of each leaf into tight contact with the post.

Brush contacts are not suited for withstanding an arc, even for very short periods, and horn contacts with a magnetic blow-out are used in conjunction with them. Carbon arcing tips were at one time used to some extent for contactors, as they are still employed for circuit breakers; but their perishable nature has rendered their use practically obsolete.

¶ Magnetic Blow-outs.—The term 'blow-out', with the suggestion of an operation similar to the extinction of a candle, has tended to clothe with mystery the simple action of the magnetic field upon an arc, with the result that the design has at times been based on incorrect principles. In reality the effect is exactly the same as that of a magnetic flux upon any other conductor carrying a current. In other words, the blow-out system constitutes a motor with the arc as the armature conductor, moving in a direction that can be predicted by Fleming's 'hand' rule, or any of the other methods for ascertaining the movement of a conductor cutting lines of force.

This being the case, the action is seen to consist of a movement of the arc in a direction perpendicular to its length, or in such a way as to stretch it out. Hence it rapidly 'balloons' until its length is too great for the voltage to maintain, and it is extinguished. Three conclusions may therefore be drawn as to the design of the blow-out. First, it will not be effective unless a clear space is provided into which the arc can be forced; secondly, the motion will only be in the right direction if the flux is undistorted by external magnetic influences; and thirdly, a comparatively weak flux is all that is required, since the arc is a remarkably mobile conductor.

The first condition is met by providing an enclosure of a heat-resisting material, generally an asbestos composition, which is open in the direction in which the arc is desired to move. On either side of this 'arc-chute' the iron cheeks of the magnet are fixed, so as to send the flux straight through the chute, from one side to the other. It is only when the higher voltages are being dealt with that much difficulty is experienced in providing space for the arc. An instance of such a difficulty successfully overcome is given in Fig. 84, where the chutes on the three phases are alternately open on the top and in front, in order to prevent adjacent arcs from interconnecting. A typical design for a small contactor is given in Fig. 89.

The core and coil of the magnet are usually located at the back of the contacts, and a series arrangement is adopted for the coil. This not only avoids an extra circuit, but it brings about the progressive

weakening of the blow-out force as the arc extends and its resistance increases. The result is that the final rupture of the circuit is rendered the less violent, and the risk of voltage peaks upon break is much reduced.

Distortion of the flux is produced by the proximity of other masses of iron, and the chute must not be placed too close to the main core of the contactor. Even a slight inclination of the lines of force is sometimes sufficient to drive the arc to the side of the chute, where it produces a hot spot that is able to restart the arc after it has once been extinguished. This rekindling may occur a number of times in quick succes-

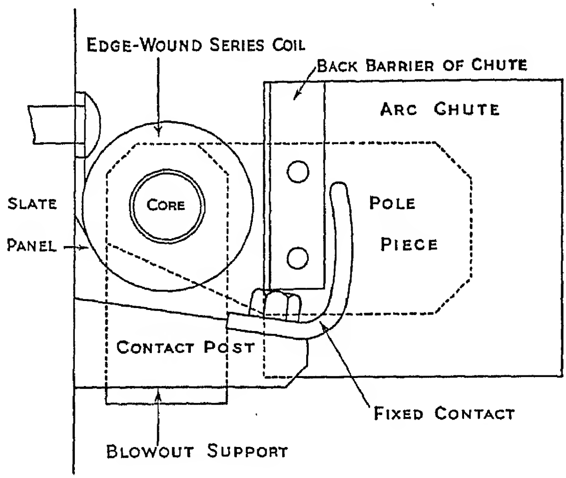



*Fig.* 89. Diagram of magnetic blow-out for a small contactor, with near arc cheek and pole-piece removed.

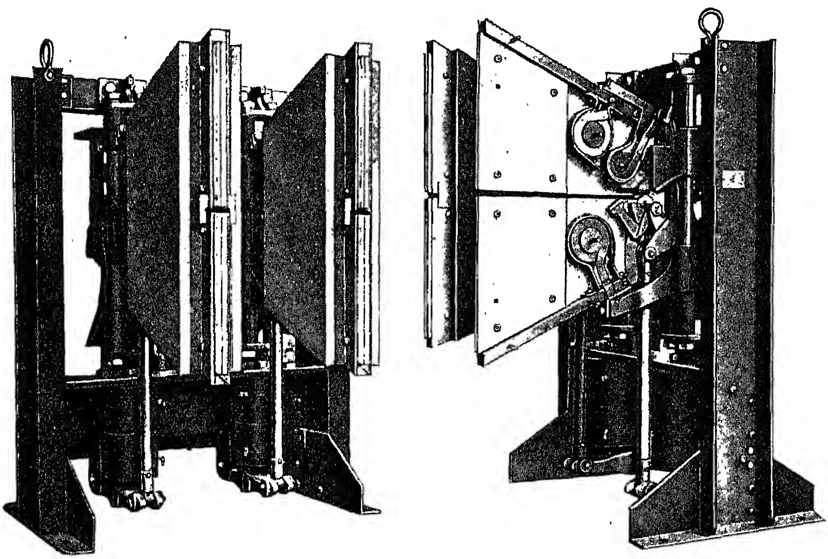
sion, as is in fact shown by oscillograph records. Such a blow-out i characterized by a tearing sound, in contrast to the clean snappy repor of a single break, the former being very destructive to the chute and th contacts.

Restriking of the arc may also be produced by employing too stron a blow-out. The coil should have only about six turns for a 100-ampere and two or three for a 1,000-ampere, contactor. Alternating arcs ar the easier to suppress, since the current passes through zero twice pe cycle in the ordinary course of things, and it is only necessary for th blow-out to prevent their re-forming.

Another cause of restarting of the arc is its rotation round th 'jumping-off' point on one or both contacts due to the much strong flux there than at the remoter portions of the discharge, and the cor sequently faster movement. If any horn contacts are examined th tracks of the arc can be traced at the backs of the conducting surfaces but for small units there is little risk of its revolving farther than thi

But when the rating exceeds about 300 amperes the arc is more persistent, and if sufficient clearance is left at the backs or sides of the contacts it is apt to continue its rotation until it strikes across below the original point of formation, short-circuiting the main loop completely.

To guard against this occurrence the clearances should be reduced to the practicable minimum; while special devices are employed to urge the arc as effectively as possible in the desired direction. The fixed



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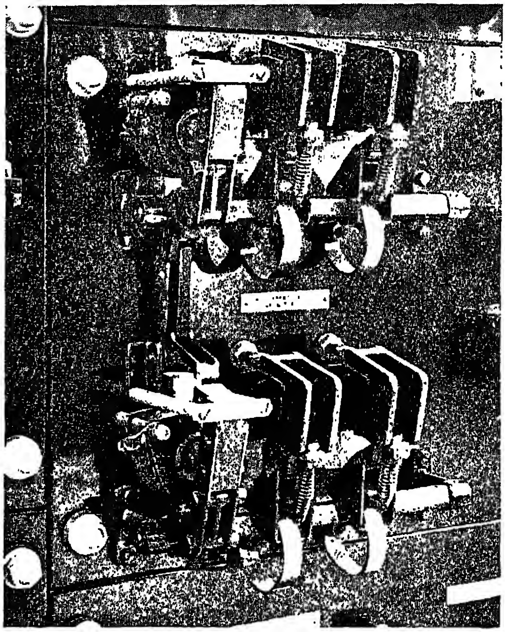
Front view. Side view (one side of arc-chute removed).

*Figs.* 90 and 91. High-power contactor, showing multiple arcing tips, blow-out coils, and barriers. Rated at 3,000 volts and 2,000 amperes for the double unit (single pole).

auxiliary horns mentioned in connexion with Fig. 84 are a case in point. Auxiliary coils are also employed to strengthen the magnetic field at a distance from the contacts. An interesting design comprising two units in series, each rated at 1,500 volts and 2,000 amperes, is shown in Fig. 91, the side of one arc-chute being removed to expose the contacts and coils. These comprise a pair of butt contacts, then an intermediate arcing tip which introduces the first blow-out coil, and a final pair of arcing tips and coils. The arc-chute is divided into two mutually insulated halves, and beyond the last tips barriers are located for splitting up and throttling the arc, thus effectively cooling it. Transverse barriers for the same purpose, and also for lengthening the arc, are employed in other designs.

With regard to the shape of the arc-chute, it is important that

pockets and corners in the path of the arc, where stray ions may be entrapped, be carefully avoided ; for these facilitate the restarting of the discharge. Such pockets are difficult to obviate in the vicinity of the fixed contact, and it is a common expedient with the larger models to lead the arc quickly away from this region by means of an auxiliary 'extension' contact placed flat against the narrow side of the chute,



*General Electric Co., Ltd*

*Fig.* 92. Two mechanically interlocked A.C. contactors with long-radius off-stop.

and fitted with a spring clip at its inner end for making the electrical connexion.

¶ OFF-STOPS.—The position of the armature when open is fixed by a stop of some kind against which it rests. Some difficulty is usually experienced, however, in checking the opening movement without causing a considerable rebound, a feature in a contactor that is highly undesirable. Its occurrence is due to the stop or the part of the armature that strikes it being of a springy nature.

The remedy is thus to render the blow a dead one, and this is promoted by locating the stop at as large a radius, and making it as far removed from being springy, as possible. The design of the parts concerned should be massive, and there should be a shock-absorbing

element of some kind to deaden the blow, such as a leather pad. The latter is especially needed in large models, in which the unchecked concussion may well be strong enough to strain or rupture the bearings after a comparatively few operations. A good example of such a long-radius stop is given in Fig. 92, where the blow is taken high up on the armature at about the same distance from the pivot as the contacts. A leather pad is interposed between the cross-piece and the armature.

Whatever type of stop be employed in the case of A.C. models, it should be possible to remove it quickly in order that the whole contactor may be opened up, as shown in Fig. 76, to facilitate repair.

¶ General Notes on Design.—One of the most troublesome problems in connexion with contactor design is the prevention of sticking in the closed position, due to residual magnetism. It is a curious fact that this phenomenon is the more serious the more permeable the iron of which the magnetic circuit is composed. Now it is the custom to make the cores of D.C. models of mild steel, which has a high permeability and hence also a high retentivity. Where the armature also is of mild steel or of a similar grade of iron, sticking is especially apt to occur.

Fortunately the residual flux with highly permeable irons is so unstable that a slight separation at or near the air-gap is sufficient to cure the trouble. This is sometimes brought about with small electromagnets by fixing a brass button or peg in the pole-face so that it prevents the armature from touching by a few thousandths of an inch. Such a method of separation is not durable enough for contactors, the hammer-blows of which will soon flatten down the projection. It will, however, be found that a coating of nickel on copper electrically deposited all over the pole-face (back as well as front) to a depth of about 0·002 in. will answer the purpose. A brass or even a paper washer of about double this thickness between the pole-face and the core will also, as a rule, produce the same result.

Rather more difficulty is experienced with A.C. contactors, which are composed of a specially permeable grade of iron, and which are excited by a current having peak values 41 per cent. in excess of the effective strength. There are no pole-faces to assist matters here, and an actual thin plate of nickel or eureka is interposed in one of the air-gaps by some firms.

Failure to open the circuit at the proper time can produce the most serious consequences of all defects. For example, it may bring about the wrecking of a machine tool or a furnace hoist. Some designs of contactor are curiously free from it without any form of separation being fitted ; but when it shows itself, then preventive means must be adopted that will place the occurrence beyond the bounds of possibility.

The armature pivot is not situated immediately beneath the centre of gravity of the moving system, but somewhat to the rear of this, in order that the weight of the whole may tend to bring the armature out smartly to the off position. More pull is necessary with D.C. than with

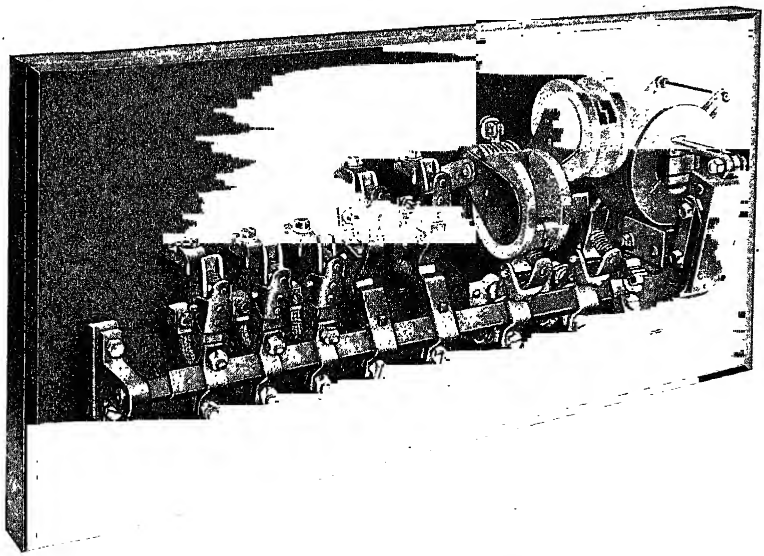
A.C. models, as the flux is slow to decay, and may hold the contacts with their tips touching for an appreciable time. It will be found, on test, that about two seconds is required for the pull of a 2,000-ampere D.C. model to disappear almost to zero, and a considerable additional opening force is needed to complete the movement after the contact springs have expended themselves. Sluggish opening is a fatal defect in the interruption of an electric circuit, and the above point therefore requires careful attention.

With regard to the support for contactors, both slate panels and an insulated steel framework are employed. The latter is especially appropriate for marine installations. When slate is used for large A.C. models, thin shock-absorbing pads, e.g. of press-pahn, should be fitted between the main supporting surface and the panel to prevent powdering of the support due to the violent blow struck by the armature.

# XII

## CONTACTOR RELAYS, INTERLOCKS, AND SWITCHES

THERE are a few cases in which contactors can be made to perform discriminating functions without external assistance, and the various types of accelerating unit described in the last chapter are examples of this capability. But, in general, contactors are not able to decide for themselves when to act, and they therefore require the services of



*British Thomson-Houston Co., Ltd.*

*Fig.* 93. 75-ampere A.C. contactor with two main, two auxiliary, and three interlocking poles.

various auxiliaries to govern their operation and to afford a check upon the apparatus in the event of any component failing to play its part. These functions are fulfilled by relays, electrical and mechanical interlocks, and various kinds of master and auxiliary switches. The first of these bring about operation automatically when a certain condition has been fulfilled, such as the falling or rising of a current to a certain value ; while the last close or open the contactors at the will of an attendant or through mechanical contact with a moving body, such as a lift cage. An interlock enables a mechanical or electrical change to be effected by the movement of one contactor or unit which either causes or prevents the movement of another. These auxiliary components of a control installation will now be described.

¶ Auxiliary Contacts.—Relays and electrical interlocks depend for their action upon the closing and opening of auxiliary contacts. Although these have ordinarily to pass only a small current, ranging from say 0·01 ampere to about 1 ampere for apparatus of moderate size, they must make the circuit with as much certainty as the main contacts. Since there is often only a small force available to press the surfaces together, the tendency in the past has been to design them on too flimsy a scale, and a certain amount of unreliability has been the result.

A common pattern consists of a small insulated copper disk, flexibly supported, and resting when in the closed position on the edges of two contact strips of copper. Such a design may be seen in Fig. 107, in which the top set of contacts is normally closed and the others normally open. Another type is shown in Fig. 93, in which the auxiliary contacts are to all intents and purposes small reproductions of the main units. Other patterns may be seen in the illustrations of complete schemes, most of which indicate the present practice of making these details more robust and certain in their operation.

¶ Contactor Relays.—The following list includes the most important relays employed with contactors, which it is proposed to consider in detail: current limit, time limit, float, pressure, overload, low voltage, inching, torque, step-back, change-over, field accelerating, field braking, field protection.

¶ Current-limit Relays.—A beginning will be made with the current limit-accelerating relay, not because it is the simplest, but because reference has already been made to it in several places in connexion with the design of accelerating contactors. The principle is that a pair of contacts, which when closed will cause a contactor to act and thereby short-circuit a step of starting resistance, are held open by a coil through which the load current passes. The relay is set to operate as soon as the load current has fallen to a certain safe value. Apart from the effect of the coil, it is held out of action, mechanically or otherwise, until the load current reaches a peak value due to the starting or acceleration of the motor, after which its action is restrained by the coil only. When this heavy current has fallen to the desired value the relay operates, and the next step of resistance is cut out. The same or a similar relay may then come into operation to cut out the following step of resistance when the further peak current has fallen, and so on for all the steps of the acceleration.

There are two general types of current-limit relay, the first of which is separate from the accelerating contactors themselves and does duty for several of the latter; while the second type is mechanically interlocked with the individual contactors, and in consequence a separate unit is needed for each step of acceleration. The former of these two types was the original pattern, and a good example that is in use at the present day is shown in Fig. 94. This has two coils, one a series winding through which the load current passes, and the other a shunt winding temporarily connected in series with the coil of the contactor which is

about to be operated, the arrangement being such that the peak current is flowing in the series coil before the shunt coil is energized. The latter then lifts its heavy plunger at one end of the lever, removing the support from the plunger of the series coil to which the relay contacts are attached, so that the latter system is now held up solely by the load current flowing through the series winding. When therefore this

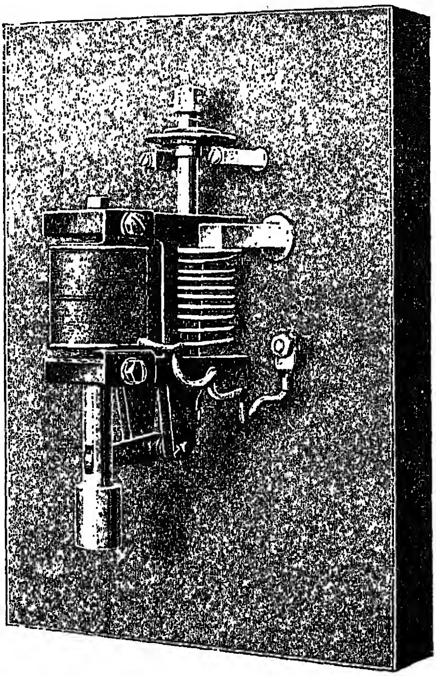


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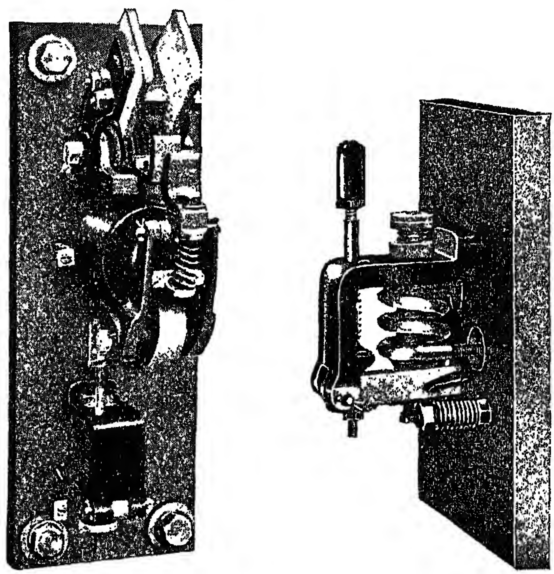
*Fig.* 94. Separate type of current-limit accelerating relay.

current has fallen to a predetermined value the series plunger is dropped, making contact for the accelerating contactor.

This relay was employed for both direct and alternating currents, but its use is now practically restricted to alternating current work on the part of one or two firms. It has the advantage that one relay will serve for more than one contactor, the usual arrangement being to fit two, which are brought into service alternately, the connexions whereby this is accomplished being shown, for example, in Fig. 130 later. In addition to there being an economy in relays there is less adjustment to be accomplished, since only two relays require setting. On the other hand, a number of electrical contacts have to be made and broken at

each accelerating contactor, and this involves a large amount of wiring on the switchboard.

An example of the second pattern is shown in Fig. 95, which shows how the relay is associated with the previous contactor to that which is required to start up. While the contactor is open the relay is mechanically held in the off position; but when this contactor closes the mechanical support is removed, and the relay is now held up entirely



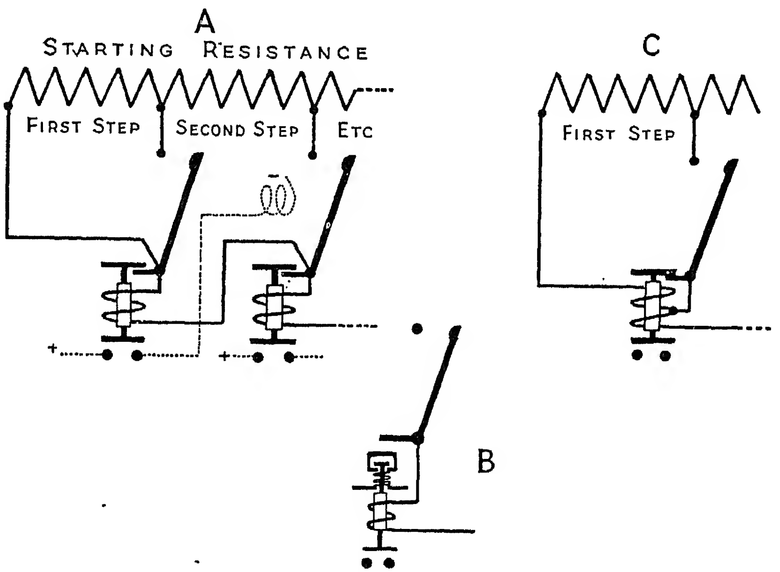
*General Electric Co., Ltd.*

*Fig.* 95. Individual type of current-limit relay. The relay itself is shown on the right, and associated with a D.C. 75-ampere shunt contactor on the left.

by the effect of the peak current. When this ceases the next contactor is closed.

This process is shown in the diagrams in Fig. 96, Diagram A being the simplest arrangement. If this be adopted as shown, however, the action of the relay will be somewhat unreliable, as it will tend to fall instantaneously unless there is a considerable peak current. The reason for this is that the mechanical support will be removed before the effect of the peak current is felt, since the latter only occurs after the contactor has closed its circuit. There are two methods in use for overcoming this difficulty. In Diagram B the contactor does not directly support the relay, the latter being held by a spring. When the contactor has closed so far that the tips of its contacts are just touching, the horizontal lower extension of the armature is just beginning to depress the spring and thus remove the support from the relay, not

freeing the latter until the actual peak current has come into being. The second method is shown in Diagram C, in which it will be seen that the relay coil is now a double one. Before the contactor closes the load current passes through both parts of the coil, and this is capable of holding up the relay under any practical conditions. As soon as the tips of the contactor have touched the upper portion of the coil is short-circuited, leaving the normal lower portion alone in circuit. As




A. Simple series. B. Spring supported. C. Double coil.

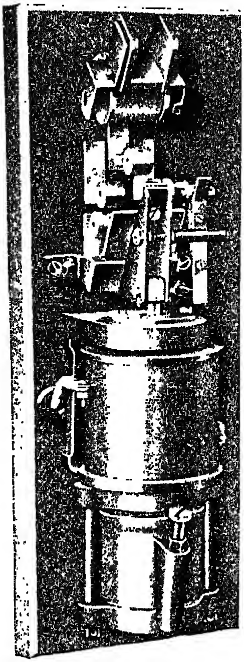
*Fig.* 96. Three types of current-limit relay associated with accelerating contactors.

before, this one drops the relay contacts when the peak current has fallen to the safe value.

The illustration shown in Fig. 95 is an example of the B pattern, in which the spring is threaded on the vertical rod which supports the relay armature. This rod is depressed by the closing contactor against the pressure of the spring, and the nut at the lower end thus removes the mechanical support from the relay armature. Relays of the C type are to be seen in Fig. 190.

The mechanically associated type is now in practically general use for the acceleration of D.C. contactors; and it is also used by many firms for A.C. equipments. Until recently distinct A.C. models with laminated iron parts were always employed for the latter; but it has lately been found that the effect of eddy currents in the iron of these small relays is so unimportant that the same model can generally be used for both D.C. and A.C. equipment.

¶ TIME-LIMIT RELAYS.—Time-limit acceleration is preferable to current limit for a number of purposes, mostly characterized by constant load conditions and therefore by a uniform rate of acceleration. Current-limit methods have one or two small disadvantages, the chief of which is that when a very light load is being accelerated the relays tend to drop too quickly and to overstress the equipment mechanically, although electrical conditions are satisfied. Time-limit acceleration obviates this difficulty. Suitable loads for the latter form of acceleration are air compressors, pumps, some forms of printing presses, the starting of squirrel-cage motors at no load, and so on.



*General Electric Co., Ltd.*
*Fig.* 97. Time-limit relay, separate type.

As with current-limit relays there are two patterns, viz. the master relay and the individual relay associated with each contactor. The former is the more usual, and resembles in general a small automatic solenoid starter energizing the accelerating contactors in turn. The usual pattern comprises a solenoid and plunger, with an oil dash-pot attached to the latter, compelling it to rise at a definite slow speed and thus close the contacts at the required intervals. An example of this type is shown in Fig. 97, in which the dash-pot is fitted immediately below the plunger and the contacts are situated above it. Other patterns more closely resemble the radial-arm solenoid starter.

In addition to the dash-pot form of time-lag, other types have recently come into use, which are largely taking its place and are introducing improved characteristics that are much widening the scope of this form of acceleration. A compact clockwork escapement, somewhat resembling the ringing movement of an alarm clock, is securing rapid adoption in some fields on account of its accuracy, ease of adjustment, reliability, and convenience. The eddy-current brake, consisting of a metallic disk, frequently of aluminium, rotating between the poles of a permanent or electro-magnet, is also employed ; while the delay imposed by compelling the relay armature to overcome the inertia of a fly-wheel is a further method. The most interesting, however, of the later time-lags is that which makes use of the decay of the flux in a small electro-magnet when its exciting coil is short-circuited. Thisprinciple is well adapted for association with small or large contactors, and by its means a combination of current- and time-limit acceleration can be carried out, which corresponds very closely with practical requirements. An example of its use is given later in Fig. 141.

An interlocked form of the time-limit relay is chiefly used when there

are only one or two contactors to be closed. It resembles the current-limit interlocked pattern closely, with a dash-pot substituted for the current coil. An example is shown in Fig. 98.

The present tendency is to extend the use of time-limit acceleration at the expense of the current-limit method.

¶ Float Relays.—Pumping motors are generally employed to fill a tank or reservoir, and it is usual to start these when the water level has

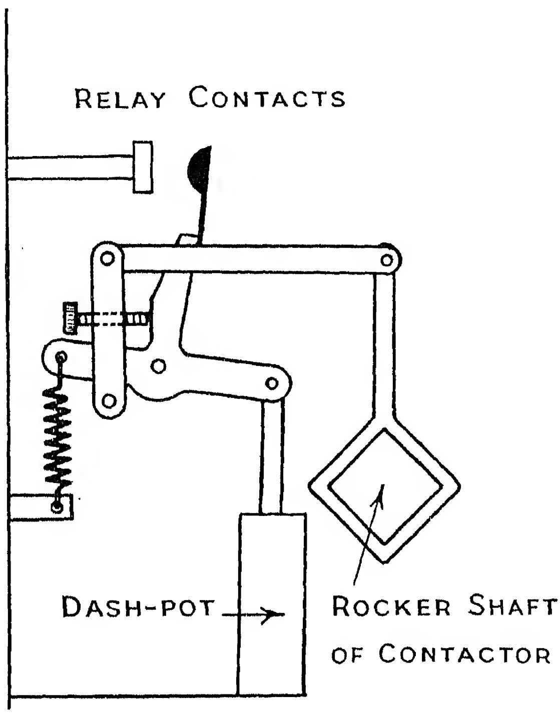


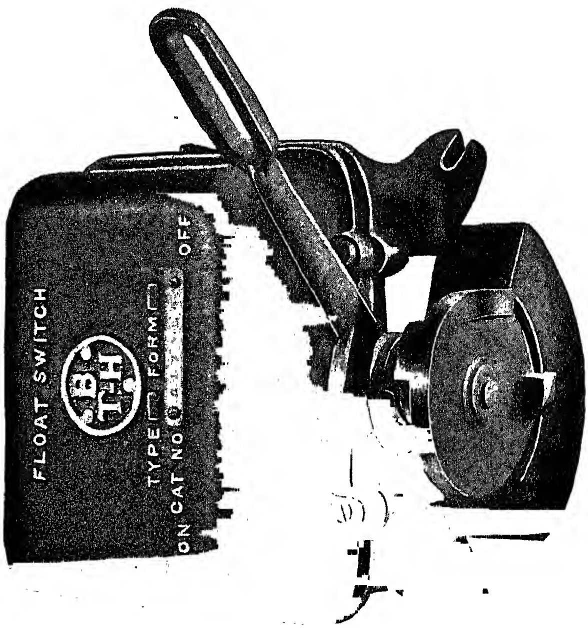

*Fig.* 98. Individual pattern of time-element relay, shown associated with A.C. contactor.

fallen to a given point, and stop them when the reservoir is full, by means of a relay. This is one of the simplest forms of automatic contact-maker, consisting as a rule of a float on the surface of the water itself, attached to a chain passing over a pulley and leading to the moving contact of the relay. A tumbler device is generally fitted, so that the chain is able to move the contacts some distance before they overbalance, and it thus either closes or opens the contacts suddenly, as shown by the example in Fig. 99.

¶ Pressure Relays.—Instead of using a float relay in the above case, a small pipe may be taken from the reservoir and caused to move the

contacts open or closed according to the pressure of the water. This is naturally a less robust form of switch than the foregoing; but it possesses advantages in some situations. It is also used for governing the operation of air compressors, as it is able to start the motor when the pressure has been reduced to a certain point and stop it when the maximum value has been attained. Such a relay is illustrated in Fig. 100, based upon the principle of the Bourdon gauge.

¶ Overload Relays.—Overload relays take the place of fuses in contactor installations. They consist of a series coil which is able to lift the




*British Thomson-Houston Co., Ltd.*

*Fig.* 99. Float switch showing tumbler device.

plunger when the current in the winding exceeds a given value, and they then open contacts which de-energize the contactors. They can be classified in two ways. First of all, they are divided into self-resetting, hand-resetting, and electrical resetting models; and, secondly, they may be grouped according as their operation is instantaneous or possesses a fixed or inverse time element.

The simple overload relay, in which the plunger falls as soon as the overload is removed, is termed a self-resetting or gravity-resetting device. In the example shown in Fig. 101 the relay will be of this type if the small lever shown at *A* is removed. The lever constitutes a species of small latch that falls under the moving part of the relay after it has been lifted, and prevents it from falling again until the handle itself

has been raised, thus converting the apparatus into a hand-resetting pattern.

An electrically resetting relay would possess a second coil, wound of fine wire, and connected to a push button or to a contact in the master controller, so that upon the coil being energized the resetting would be accomplished electrically. In the example shown in the figure this resetting may be accomplished by the lifting of the small lever by means of a shunt coil. A more elaborate pattern may be required in which the relay would be automatically reclosed once or twice upon the overload going off, but on the trouble recurring a stated number of times the

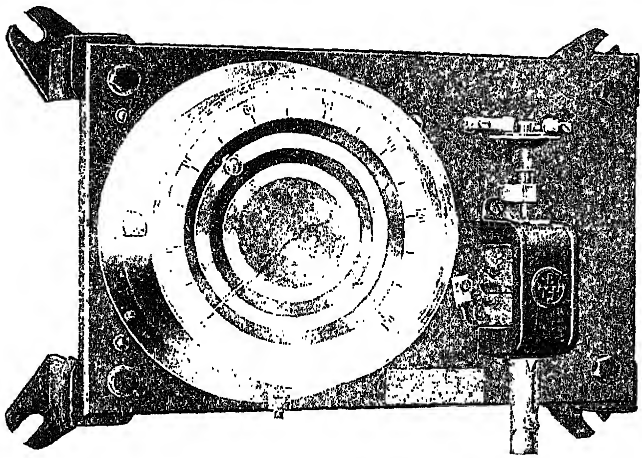


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*Fig.* 100. Pressure governor and D.C. magnetic relay in cascade.

contacts would be held finally open. This would be termed an auto-reclose relay.

If the dash-pot at the lower portion of the relay in the figure were removed, the opening of the circuit would occur immediately the overload was experienced, and the relay would be an instantaneous one. The addition of the dash-pot delays the operation by a period which is the smaller the greater the overload, and the protection is thus termed 'inverse time element'. A fixed time-element relay would be one in which the time-lag would be constant whatever the degree of overload, and this would be accomplished by causing the relay to set in motion an independent dash-pot or other form of time-lag which interposed a fixed delay before tripping was accomplished; or a self-contained apparatus could be constituted by merely interposing a spring between the plunger and the dash-pot. A definite tension would then be brought to bear on the time-lag device whatever the extent of the overload.

¶ Low-voltage Relay.—Any contactor installation may be said to possess a form of low voltage protection, since the contactors will all open

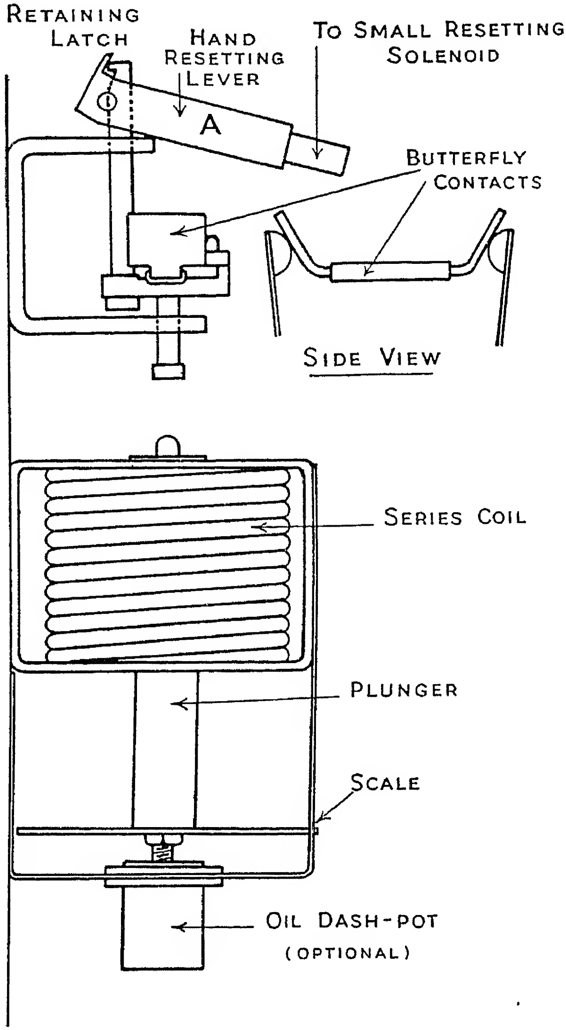



*Fig.* 101. Overload relay for gravity, hand, or electrical resetting; and for instantaneous or inverse time-element operation.

when the voltage has decreased below a certain point. This kind of protection would have the drawback that it would cease as soon as the voltage revived, and for many purposes that would be a dangerous occurrence.

For example, it is easy to understand that an unexpected shut-down might be utilized by the operator as an opportunity for overhauling some part of the gear, and if it were liable to restart when he was not expecting it, he, as well as the apparatus, might be seriously injured.

In order to prevent the unexpected resumption of operations an additional device is frequently added, which may take the form of a special relay. This may be a separate small contactor, connected as indicated in Fig. 102. The exciting current for all the coils of the main contactors will pass through the contacts of this auxiliary unit, and it is closed by some such method as a spring-off switch, i.e. one that is closed only as long as it is held down by the operator. When, however, the contactor closes the auxiliary contacts shown below the armature

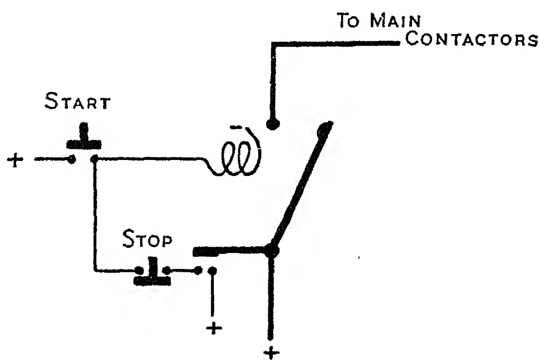



*Fig.* 102. Low-voltage protective relay or arrangement, showing spring-off start and stop buttons.

are brought together, causing the unit to make its own holding circuit, and it therefore remains closed after the original starting current has been cut off. Upon failure of the voltage this contactor will open and will remain open, a separate operation of the starting switch being required to put the gear into commission again. Instead of using a special contactor these holding contacts can be added to one of the main line contactors.

In order to stop the motor a spring-off stop switch, the reverse arrangement to that used for starting, is located in the holding circuit of the contactor carrying the holding contacts, this switch being normally closed and remaining open only while it is depressed by the operator.

As it is advisable to distinguish between the two forms of low-voltage operation, that which merely opens the circuit, permitting it to reclose of its own accord upon the revival of the potential, is termed 'low-voltage release'; while the type which remains open is known as 'low-voltage protection'.

In some cases, such as occur in mine-hoist practice, it is required

that the no-volt protection shall not come into operation until after a certain interval, during which the voltage is given an opportunity of recovering. Time-element low-voltage relays are designed for these situations ; and since the delay is relatively small, it may conveniently be provided by the inertia or fly-wheel type of time-lag.

¶ INCHING RELAY.—Many motors require to be rotated through a small angle as a preliminary to being set into permanent motion. This operation is called 'inching', and is employed when setting up machine tools, when feeding the paper into printing presses, and for other

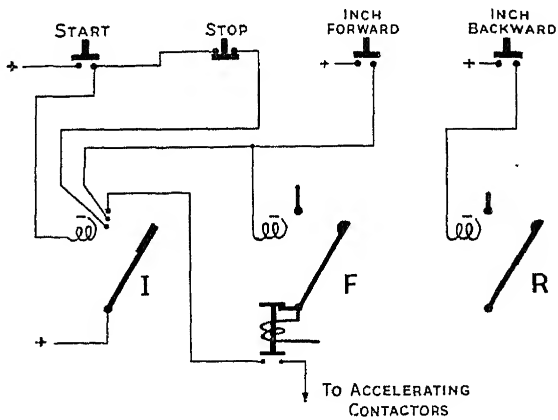
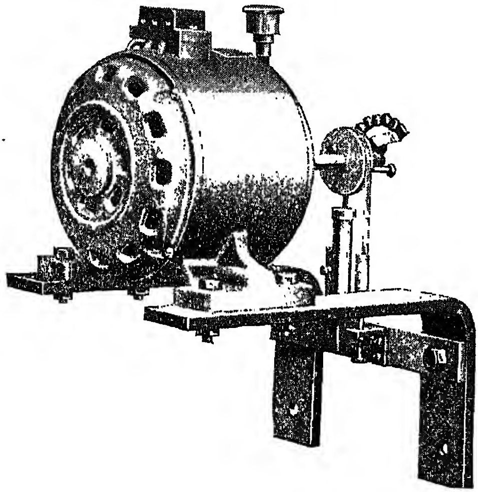



*Fig.* 103. Diagram of connexions for inching contactor (*I*), showing relation to forward (*F*) and reverse (*R*) line contactors ; normal running provided in forward direction only.

similar functions. Inching is generally carried out by means of push buttons similar to the first of those that have just been described, the motor rotating at slow speed while the switch is depressed and stopping as soon as the pressure is released.

In order to accomplish this it is necessary to prevent acceleration by positively disconnecting the accelerating contactors, and also to put out of action the low-voltage apparatus. This is usually accomplished by the same relay as affords low-voltage protection, and the example in Fig. 103 possesses the contacts for the whole function. There are three insulated contact posts and three contact fingers attached to the relay armature, of which one closes the holding circuit as already described, the second goes to the line contactors, which close the circuit for the motors through the whole of the starting resistance, and the third makes the exciting circuit for the accelerating contactors. For inching this relay is left open, and the appropriate line contactor only is closed by means of the spring-off switch. In cases where the inching movements are always of very short duration, it is often permissible to omit the provision for cutting out the accelerating units.

¶ Torque Relay.—For some purposes, notably when using a contactor installation as a ' slip regulator ', contactors are required to open as the current in the motor circuit increases. For example, when employing an induction motor with a fly-wheel in order to counteract heavy fluctuations in the load, it is necessary to cause the speed to decrease on the occurrence of an overload to enable the fly-wheel to give up some of its energy. This may be accomplished by connecting the contactors to contacts which are successively closed by a relay acting against the force of a weight or spring. The illustration in Fig. 104 shows such a device, consisting of a small induction motor, the stator of which is



*General Electric Co., Ltd.*

*Fig.* 104. Torque relay.

series wound and is supplied by means of current transformers connected in the main leads. The moving contact is mounted directly upon the shaft of the squirrel-cage rotor, but is prevented from rotating until normal load has been exceeded by means of a long spring and dash-pot, the latter of which serves to damp the movement of the relay. As the overload comes on the contact arm of the relay moves over, and opens contactors introducing successive steps of resistance into the rotor circuit of the driving motor, causing the fly-wheel to give out more and more energy until the peak load has ceased.

The particular requirement of this relay is that the moving parts must be as free from inertia and friction as possible. The use of a spring accords with the former condition, and it has the additional advantage that the force it exerts may be made to increase at any desired rate as the steps of resistance are cut out. If the force is sensibly constant over the whole range the whole of the overload will be taken

by the fly-wheel, the motor being protected against more than the normal load. It is, however, rarely necessary to fit a sufficiently heavy fly-wheel for this duty, and it is usual to require the motor to take a certain percentage of the overload. By designing the spring so that a greater load is required for bringing about the opening of each successive contactor, a greater and greater proportion of the overload is imposed on the motor.

The example shown in the figure controls a 500 H.P. induction motor driving a rolling mill, the whole installation being shown in Fig. 167 in a later section.

¶ Step-back Relay.—It is sometimes required that upon the occurrence of an overload exceeding a certain value the controlling resistance shall all be cut into circuit with the armature, thus reducing the speed to the starting value. This is accomplished by means of what is called a 'step-back' relay, which closely resembles the overload relay in design, the contacts being so connected that the exciting circuit for the accelerating contactors only is interrupted.

¶ Change-over Relay.—When a change of connexions is required, such as when changing over from star to delta connexions for the starting of a squirrel-cage motor, or when using an auto-transformer method for effecting the same purpose, a change-over relay is employed. This resembles a small contactor in which two sets of contacts come into operation, one set while the armature is in the open position and the other after it has been closed. Since the exciting currents only of the contactors are dealt with the contacts need not have a long travel, but there must be a certain amount of pressure between the contacts which are closed when the armature is in the open position. This is usually provided by means of a spring.

¶ Field Accelerating Relay.—When a field rheostat is employed for governing the speed of a D.C. motor, it has been shown to be most important that starting should not be effected when the field is weakened. This may be automatically taken care of by means of a relay which short-circuits the field rheostat when a current above a certain value flows through the relay coil. The latter is series wound and is connected in the armature circuit. If it be supposed that the motor is being started with a considerable amount of resistance in the field, the heavy rush of current upon switching in will cause the relay to close its contacts. At the end of the starting operation the peak current will fall to normal and the relay contacts will open, cutting in the field resistance. If this causes the armature current to increase considerably, the relay armature will again be attracted; and this action will be continued, the relay vibrating somewhat after the manner of a Tirrill regulator until the motor is accelerated to the speed for which the field rheostat has been set. Such a relay is shown in Fig. 105, in which the method adopted for suppressing the arc across the contacts can be studied. It is important for the satisfactory operation of this relay that

the current shall be broken as quickly as possible, and a magnetic blow-out is hence employed for the purpose.

¶ Field Braking Relay.—A motor that is brought to rest by means of a dynamic brake has the braking almost cancelled if the line voltage fails. One way of remedying this defect is to connect the armature in parallel with the shunt field when the potential goes off, and this may be effected by a small relay in which a shunt coil connected across the main leads holds upon a pair of contacts against the tension of a spring which would effect the above connexion if the voltage were to fail. A third contact is held closed by the coil, and completes the circuit for the field in the usual way. This latter contact is necessary since the ordinary path for the field must be kept open until this relay has closed, otherwise there would be a short circuit when the voltage is first applied.

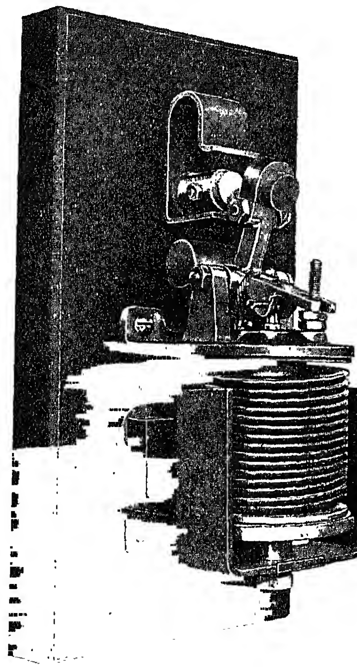


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*Fig.* 105. Field accelerating relay, showing carbon contacts and permanent blow-out magnet.

¶ Field Protective Relay.—It has already been pointed out that the effect of a break in the field circuit of a shunt motor may be disastrous, and such an event is frequently provided against by the use of a relay which opens the armature contactors when the field current fails. This is quite simply brought about by connecting the exciting coil of the relay in series with the shunt winding of the motor.

If there is in addition a series field giving a compounding of more than about 20 per cent., the current in the shunt winding will be affected by changes in the series current, through transformer action. For example, a sudden rush of current, as at starting, will weaken the shunt field considerably, and to prevent this operating the relay it is fitted with a short-circuited copper damping winding, which sufficiently delays the change of flux in the relay magnet.

¶ Interlocks.—Interlocks are for the purpose of ensuring that a series of operations takes place in the correct sequence; and they accomplish this by holding up the process if one component is not functioning correctly. It is not proposed to enumerate every type of interlock, as their employment may be made clear by one or two representative

examples. Of these the most usual is the locking open of one of a pair of reversing contactors if the other is already closed, the purpose being to avoid the dead short circuit that would occur if both were permitted to close simultaneously.

Interlocks may be of two general types, namely, mechanical or electrical. The former do their work by interposing a mechanical barrier to prevent the armature of a desired contactor from moving; while the latter prohibit closing by interrupting the circuit of the closing coil. It is a general rule that when other things are equal a mechanical interlock is preferable for an electrical installation, since the two methods are not likely to be deranged by the one mishap. Whatever

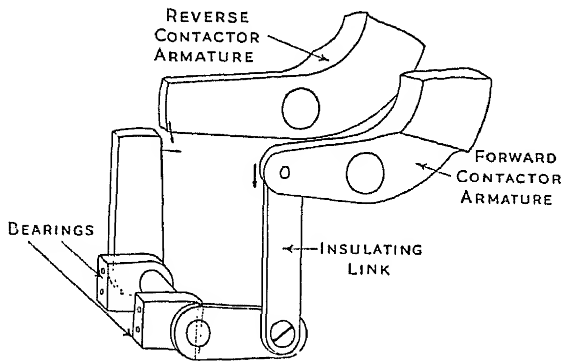



*Fig.* 106. Positive mechanical interlock for reversing contactors (panel omitted); by the General Electric Co., Ltd.

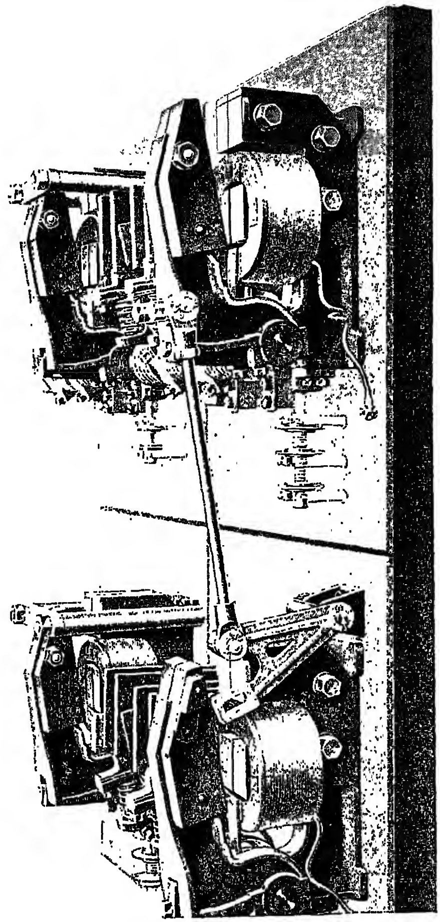
the general form, it is necessary that simplicity, robustness, and reliability be secured.

As an example of a mechanical interlock the problem already mentioned of preventing two contactors from closing simultaneously will be considered. If the units be mounted alongside each other, a seesaw lever may be pivoted between them so that either armature when closed presses against one end of the lever, forcing it to the limit of its movement in one direction. The other end of the lever will then be brought against the corresponding part of the other armature, and will definitely prevent it from executing a closing movement. This interlock has the advantage of simplicity, as well as robustness, and a fair measure of reliability. It forms part of the equipment shown in Figs. 77 and 190.

It has a small drawback, however, in that it is not absolutely definite; for although when one of the armatures is completely closed the other cannot move, the device does not prevent both being in an intermediate position at the same time; and it is just possible that both contactors may conduct the current in this position. For example, if the switch controlling a pair of reversing contactors be thrown suddenly over, the outgoing contactor may be still arcing when the tips of the other have

touched, and thus a short circuit would be brought about. Care is taken in designing the units that the clearances and the length of break at the contacts are sufficient to render this unlikely ; but the interlock shown in Fig. 106 is worth noting in that this possibility is quite avoided. An interlock for units placed one above the other, having similar advantages, is shown in Fig. 107, and a somewhat different version was illustrated in Fig. 92.

The principle of this device is that two levers are mutually located so that they get in each other's way as soon as either begins to move. One is connected to each armature, and they are so situated that they move at right angles and towards each other. Consequently a very small movement on the part of either will interpose an absolute impediment to the movement of the other. It will be seen, however, that this design is slightly inferior to the other as regards simplicity.



*British Thomson-Houston Co., Ltd.*

*Fig.* 107. View of mechanical interlock between A.C. contactor units.

The same function would be carried out electrically as illustrated in Fig. 108. Here it will be seen that the exciting current for one contactor is taken through a pair of contacts which are held closed by the other when the latter is open. Consequently, after the latter has once left the 'off' position, the exciting current for the other contactor is broken. This is a very simple method, and is much used. Its principal drawback is that it introduces an extra set of contacts which require care, and which may conceivably give trouble through failing to conduct.

Another example of interlock is that between live apparatus and a door, prohibiting the latter from being opened while the electrical gear

is in action. An electrical interlock is also employed in time-limit control equipments. In these all the accelerating contactors are provided with contacts through which the exciting current for the line contactors has to pass, the circuit being only completed when all the former are in the open position. Such an equipment is shown in Fig. 132.

¶ Contactor Switches.—A comparatively large number of switches are employed with contactor installations. These range from the master controller, whereby an operator can cause the automatic gear to execute a number of complicated operations, to the limit switch, whereby the control gear is put out of action if a given position is overrun. Between these two there is a considerable range of auxiliary switches having a variety of uses.

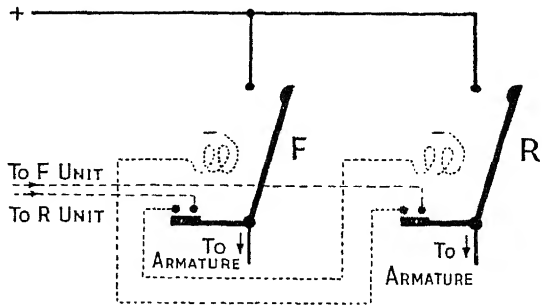


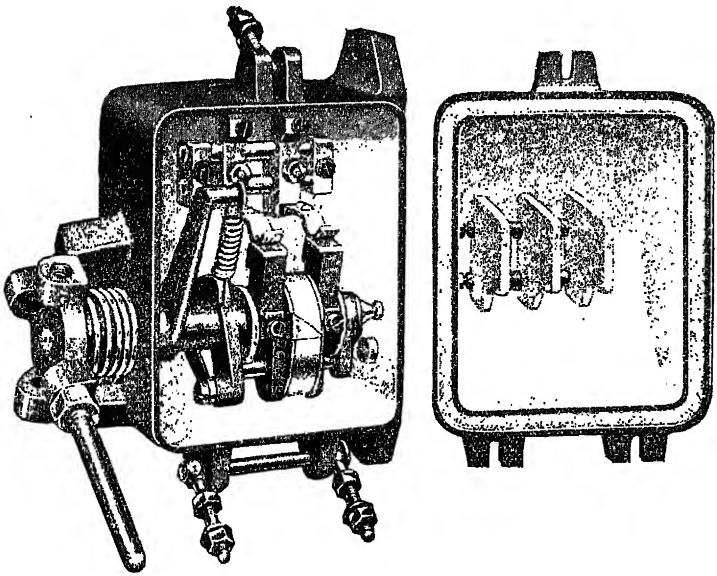

*Fig.* 108. Electric interlock for reversing contactors.

The limit switch will be dealt with first, since it is the simplest in design and purpose. It is employed on lifts, hoists, machine tools, and in other situations where damage can be caused by the overrunning of a moving part of the equipment. The function of the limit switch is to open the exciting circuits of the appropriate contactors, and frequently also of a solenoid brake, in order that a definite stop may be brought about following incorrect operation of another part of the equipment or of the operator, constituting the cause of the overrunning.

A typical design for a limit switch may possess two stationary finger contacts, which are normally joined by a brass tongue forming the moving contact, clamped to a square shaft insulated with micanite. A lever on the end of the shaft, external to the case, comes into engagement with a projecting striker on the moving part (e.g. the platen of a planing machine), and opens the switch for either direction of travel. For some purposes a quick break is important, especially when the current passed by the limit switch is large. This is readily obtained by the addition of a toggle spring, as shown by the example in Fig. 109, which has in addition a quick make characteristic. Such a model can deal with 20 or 30 amperes, and can thus be included in the main

circuit of many control equipments, a position in which the safeguard is effective even if a line contactor sticks.

A master switch is one which is designed to set in motion the complete function of the control gear, and is operated by the moving part of the equipment itself. For example, a reciprocating machine tool would be provided with a link and lever mechanism, capable of adjustment for regulating the travel, which would throw the switch over a short distance before the end of the stroke, and thus bring about the reversal of the motor.



*George Ellison.*

*Fig.* 109. Quick make-and-break limit switch.

Such a switch would require to be of more durable design than most limit switches, since it has to be in operation continuously, and therefore must be capable of sustaining a considerable amount of wear. For this reason it is designed on the lines of a controller drum. A simple example of this type of switch is shown in Fig. 110, in which the circuit is broken by the partial rotation of the drum. Here the purpose is to change the speed of the motor by opening a contactor short-circuiting part of the field resistance, requiring only two contact fingers and a single drum sector. This switch is employed for such functions as accelerating the motor when a machine tool is ' cutting air ', i.e. travelling idly between two surfaces which have to be machined.

The master switch proper is practically always a reversing unit, and would have at least three finger contacts, one of which would be joined alternately to the other two.

A master controller is illustrated in Fig. 111. This is very much like the usual drum controller for directly controlling electric motors, but

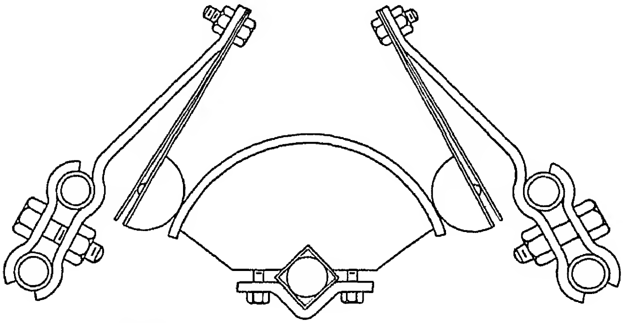
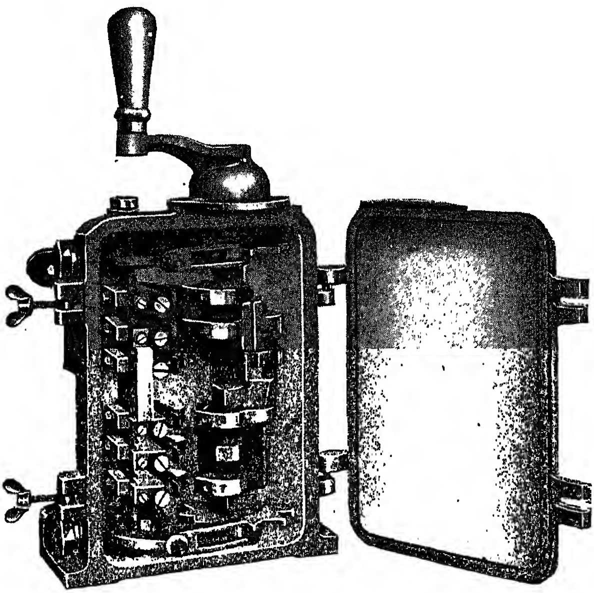


*Fig.* 110. Side view of simple drum-type auxiliary or master switch.



*General Electric Co., Ltd.*

*Fig.* 111. Master controller.

differs from it in two respects. In the first place, the currents to be dealt with are much smaller, being merely the exciting current of the contactors instead of the full motor current; and, secondly, the controller simply makes a contact for the appropriate contactor in each instance, which is a less complicated procedure than making the complete circuits for the motor.

The type shown in the figure is for the purpose of closing first the line contactors, to give the slowest speed, and then the accelerating contactors, providing for a pause if desired at two further stages before full speed has been reached. The line contactors are closed by two of the three upper contacts, one of which makes the line connexion for all the contactor coils, while the third is employed when running in the reverse direction. If the controller is thrown right over to the full 'on' position, the accelerating relays will speed up the motor at their maximum rate; but if the controller handle is paused at any intermediate stage, the accelerating contactors beyond this point will be prevented from operating, and a partial speed is thus given.

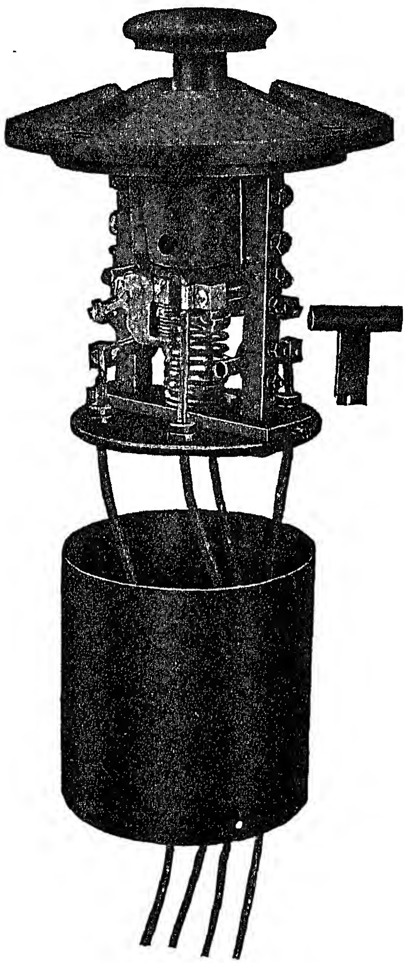


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*Fig.* 112. Pedal switch (switch cover lowered).

There is a special feature in connexion with this controller that is worth noting. The great majority of such control gears only need partial speeds before the maximum speed has been reached, a direct return to the off position being effected for stopping or reversing. If this is done by the usual type of controller drum, the accelerating contactors are opened before the line contactors, since they have to close in the reverse order. The result is that the circuit is broken at both sets of contactors, occasioning burning on all the contacts, and requiring a magnetic blow-out on each unit.

In such a case a great advantage would be secured by making the line contactors break before the others. This is accomplished in the design shown by making the lower portion of the drum distinct from the upper, and connecting the two mechanically by means of a pair of dogs, which allow a certain amount of lost motion in each direction. Not only, therefore, do the accelerating contacts lag behind

the line elements for closing but also for opening, and the desired end is thus simply attained. Other examples of master controllers are given in the chapter dealing with Electric Cranes (Chap. XX).

For many purposes a much less elaborate switch than the foregoing is sufficient for starting the operation of automatic control gear. In the case of machine tools, lifts, and mine hoists, for example, it is only necessary to close a single contact to put the gear into action, and it is a common practice to carry this out by means of a simple push switch. The principle has already been described whereby starting and stopping, as well as inching in both directions, are brought about by the agency of spring push-buttons, and most machine tools are operated by the mere pressing of appropriately marked pushes, such as those illustrated in Fig. 211, situated in one or more convenient situations.

It sometimes happens that the switch is more conveniently actuated by the foot, and this is the case with the control of wharf and deck capstans, banding lathes, &c., the device then becoming a pedal switch, an example of which is shown in Fig. 112.

# XIII

## ELECTRIC BRAKING

THE question of arresting the movement of an electrically driven apparatus in the proper manner is frequently as important as that of setting it in motion. Unlike some other prime movers, such as the internal combustion engine, there is very little inherent friction in the moving parts of an electrical machine, while there is a considerable amount of inertia; and under most circumstances the armature or rotor will continue to rotate for quite a lengthy period after the current has been cut off, rendering necessary some external means for checking the motion when a more or less rapid stop is demanded.

Now braking is desired for either of two reasons. In the first place, a quick stop is necessary for a number of loads which are not ordinarily brought to rest by their own power consumption or by inherent friction. There are, it is true, many cases where no braking is necessary, such as the pump, lathe, and grinder; for with the first the power consumed by the load would quickly bring the moving parts to rest; with the second there is little inertia as compared with the friction of the bearings and gearing; and with the third a stop within a definite period is not needed. But with others, such as reciprocating machine tools, the quick cessation of movement when the working stroke is completed is important from several points of view.

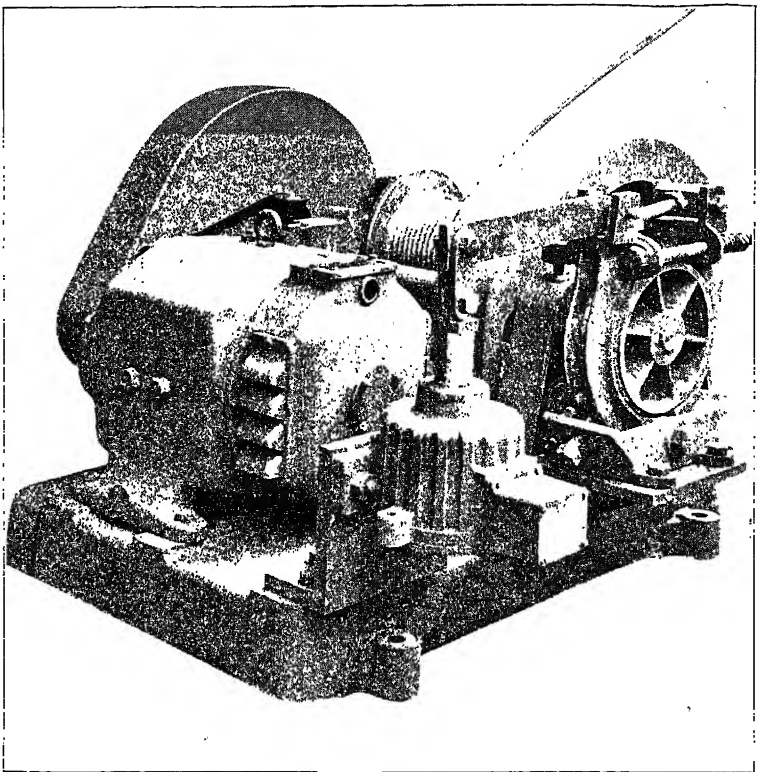
Secondly, the limitation of speed to a desired value is required for some pieces of apparatus during the light-load periods of their cycle. The lowering operation of a lift or hoist is a case in point, in which the energy given off by the descending load has to be used up in order to keep the velocity within safe limits.

Braking can be automatically applied to an electrically driven apparatus either by a mechanical brake which is operated by electrical means, or by one of the methods of electrically loading the motor, functioning temporarily as a generator, a type of retardation to which the general term of 'dynamic' braking has been given. The word is, however, often applied especially to the disconnexion of the motor armature from the line and its reconnexion to a resistance, through which it is made to generate current; and this restricted meaning will for convenience be adopted herein. For 'regenerative' braking the motor is not disconnected from the line, but the existing connexions are so arranged that the motor operates as a generator, returning power to the mains. 'Plugging' is among the simplest of braking methods, consisting simply of reversing the armature connexions, so that it endeavours to revolve in the opposite direction.

Before proceeding to describe the three methods in detail the requirements of an ideal electrically applied brake will first be considered. The most important of these is that it must not be likely

to get out of order; for since it is a safety device it must be itself thoroughly dependable. It must therefore be as simple as possible, and must not be subject to any rapid loss of adjustment through wear.

Secondly, the braking effect must be decisive, since the inertia of the motor and the connected load is frequently great. This inertia must be quickly overcome in order to economize time, and for other reasons.



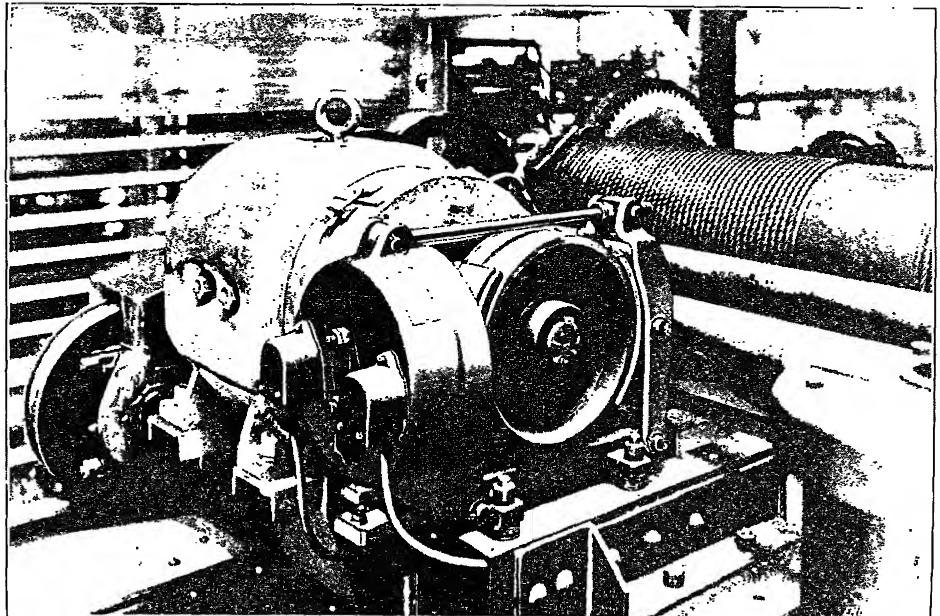
*Witton-Kramer Co., Ltd.*

*Fig.* 113. Solenoid operated band brake attached to goods hoist.

Thirdly, the action must be uniform in order that the moving parts may be brought to rest within the same distance and in the same period of time on every occasion. The reason for this will be realized if the action of such a load as a planing machine or a lift be considered, in which the motion is required to stop at a definite point at each travel.

Fourthly, the method must be economical in that it must not consume an appreciable amount of power, and must not involve any undue expense in other directions.

Fifthly, the braking method must not cause any deteriorating effect

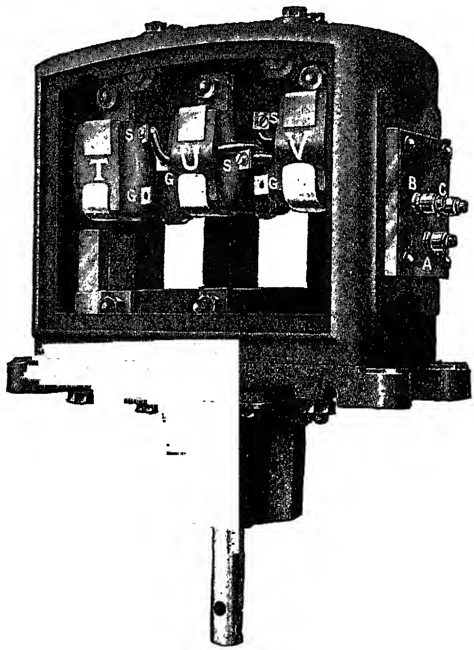


*Igranic Co., Ltd.*

*Fig.* 114. Solenoid shoe brake, attached to the main hoist motor of a 30-ton crane.

on the motor. Mechanically, its action must be smooth, in order that the shaft and windings may not be damaged by sudden alterations of speed. Electrically, the passage of braking currents through the armature must not result in overheating.

Finally, whatever additional gear is required to produce the braking must be compact, in order that its application to a piece of plant may not seriously increase the bulk or floor area of the latter.



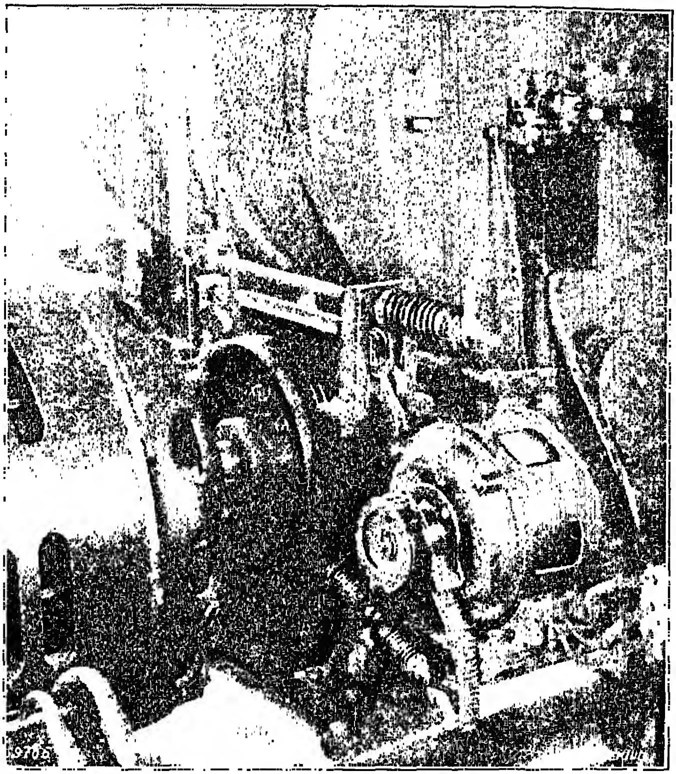

*British Thomson-Houston Co., Ltd.*

*Fig.* 115. Three-phase brake magnet, with covers removed. The bottom cast-iron cover contains an adjustable dash-pot. The three laminated plungers are shown in the lowered position.

¶ Solenoid Braking.—A beginning will be made with the mechanical brake operated by a solenoid, on the score of its simplicity. It is generally a band brake for small or moderate sizes, which is pulled either on or off by a solenoid. This pattern might be arranged with the plunger of the solenoid directly attached to the brake itself, so that it could be pulled on by the passage of the current through the coil, the amount of braking being controlled, if desired, by means of a rheostat. It could then be used not only for sudden stopping, but also for speed control during periods of negative load ; but it would become inoperative if the power were cut off. The action is therefore practically always reversed, in that the brake is applied by spring pressure or by weights, this mechanical force being held off by the pull of a solenoid, which is continuously energized while the potential is applied. But when the motor, and with it the brake solenoid, is cut off from the line, the mechanical force is released, and the brake is imposed automatically. An example of such a mechanism is given in Fig. 113,[1] in which the brake is applied by two adjustable springs, one of which is seen at the extreme right of the illustration.

[1] This illustration and those used for Figs. 114, 116, 117, 118, 119, and 122 are taken from *Engineering* by permission of that journal.

The weights are frequently made adjustable, and take the form of thick disks of cast iron, termed 'cheese-weights' from their form, and these are added one by one to a supporting hanger when the apparatus is first erected. They may be housed in a vertical drum containing sufficient oil to cover them, acting as a dash-pot and damping their movement.



*Igranic Co., Ltd.*

*Fig.* 116. A.C. shoe brake operated by torque motor.

The shoe type of brake also is easily adapted for electric operation, and in this form it is especially suitable for machine tool control and for situations where head-room is limited. A typical arrangement is shown in Fig. 114, in which the power is again applied by means of a solenoid, this being now situated behind one of the shoes. A short but powerful spring is fitted inside the same enclosure, which is kept compressed by the solenoid while it is excited. Adjustment of the spring pressure is readily effected by means of the nut at the back of the solenoid casting.

The examples hitherto given have been constructed for use upon

D.C. circuits, and the design of the solenoid will require modification if it is to be energized by A.C. In the first place the iron circuit, including the plunger and the whole of the magnet, must be built up of laminations in order that eddy currents may be avoided; and this enforces a rectangular shape for these components. Secondly, the solenoid will emit a continuous and unpleasant buzzing unless it is made polyphase, or a split-phase arrangement adopted, such as a 'shading ring' encircling rather more than half the flux at the air-gap. The characteristics of the A.C. pattern are rather different from those of the D.C. also, owing to the reduction of the reactance as the plunger moves out and increases the air-gap. This causes a very heavy current to flow at the instant of closing the circuit, and brings about a suddenness of action without the need of economy switches or series resistances. The initial current peak (of about four to eight times normal) may, however, be troublesome in exceptional cases. A three-phase brake magnet is shown in Fig. 115.

A radically different method of dealing with A.C. working is illustrated in Fig. 116, where a similar brake to that in Fig. 114 above is operated by a small induction motor, the simple gearing being so designed that two revolutions of the rotor are required for the complete travel of the brake shoes. This type of motor has practically no time-lag and needs very little attention, and its use for such a device is thus quite in order.

In addition to the adjustment of the spring pressure, provision must also be made for taking up the wear of the rubbing surfaces. It is most important that the adjusting screws or nuts for this purpose be placed in an accessible position, and be attended to with sufficient frequency, as a relatively small loss of material is often enough to decrease the braking effect very considerably. The means of adjustment in the examples illustrated can easily be distinguished, and will be seen to comply with this condition.

The excitation of the magnet may be provided either by a shunt or by a series coil. It is not a difficult matter to decide when to use each of these, according to the type of operation required, examples of both being given in equipments figuring in later chapters. The series winding is the more fully automatic, as it does not need an auxiliary switch to connect and disconnect it. In general the coil is designed to develop sufficient force to pull off the brake when the power of the motor exceeds 40 per cent., and to hold it off until the load has fallen to 10 per cent. of normal. As far as heating is concerned, it is good practice to design series windings for either half-hour or one hour duty, depending on the nature of the load to be handled. The coil itself, being wound of thick wire, is relatively cheap and robust; and little trouble is experienced with voltage peaks on switching off, or with delay in operation.

For many installations, however, so automatic a scheme is not appropriate, and in particular it is not always desired that the mechanical brake shall be applied whenever the load falls below the stated limit. A shunt-wound solenoid is then adopted, which is definitely cut out of

circuit when the brake is required to function, usually after the motion has been arrested by dynamical means, or in cases of emergency. Such a winding may need to be designed for continuous duty, and should in any case be capable of pulling off at 80 per cent. of rated voltage. A shunt-wound solenoid is alone admissible for all ordinary A.C. equipments.

In carrying out the electrical design due regard should be had to the considerable delay in braking to which D.C. shunt units are liable through the slow decay of the magnetic flux following the switching off

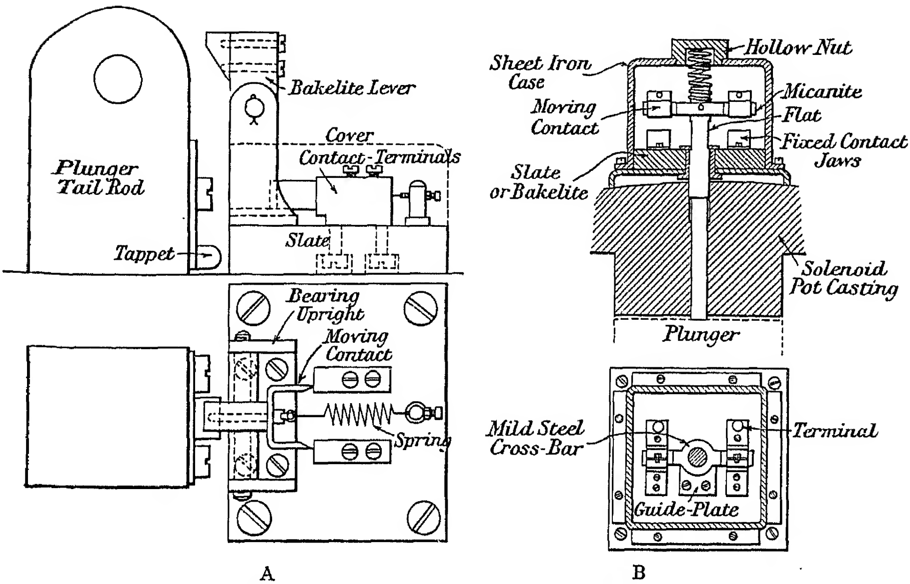



*Fig.* 117. Two economy switches for brake magnets.

of the exciting current. Now the plunger is retained for the longer time after the cessation of the magnetizing current, the stronger the magnetization that has been induced, and care should be taken that the latter is not greater than is necessary for the task of opposing the mechanical force that holds the brake off. The current required to lift the plunger from the 'off' position is, however, a relatively large one, and a considerable advantage can be gained by the weakening of this current just before the plunger has reached its final position, through the automatic insertion of an economy resistance, reducing the magnetizing force to that just required to hold the plunger. Two forms of switch suitable for this purpose are illustrated in Fig. 117, of which that shown at A is suitable for use with a large solenoid and consists of an auxiliary switch that cuts in and out resistance by means of a contactor, while B shows a switch for handling the whole of the current, which

would be specially applicable to a comparatively small solenoid. The former pattern is shown fitted to a prolongation of the plunger through the top of the solenoid pot, while the second pattern is fitted to the top of the pot itself, there now being no tail rod, and the switch being opened as the plunger reaches the top of its stroke by means of a small tappet rod inserted through the casting.

A simpler method of hastening the decay of the flux and thus quickening the braking action is to reduce the relative amount of inductance in the coil circuit by means of a permanent series resistance. If the brake solenoid is simply connected across the line it will possess the maximum inductance as compared with the inherent resistance of the coil; but if external resistance is added in series with the winding the desired result is obtained. For this reason it is a common practice to design the coil for only one-half the line voltage, and to dissipate the remainder in a series resistor.

On account of the considerable self-induction possessed by such a coil a shunt discharge resistance is usually necessary, especially if no series resistance is employed, in order that the terminals may never be open-circuited. This may be either permanently connected or switched in just before the circuit is broken, by means of contactors or a direct acting switch. In further reference to the welfare of the coil, it should also be remembered that a metal pot is liable to sweat internally, due to changes of temperature and atmospheric pressure, and the greatest care should be taken to drain and ventilate it efficiently; otherwise there will be frequent break-down of the insulation through damp. The lead-in wires for the coil are preferably situated at the top, as these form the weakest part electrically of the whole winding. If they are situated at the bottom they will not only have to sustain the whole weight of the coil, but will also be exposed to any moisture that may condense and find a lodging there.

It is the general rule to give any type of solenoid brake a retarding torque equal to the normal full-load torque of the motor, and this can be readily obtained from the formula:

$$\text{Torque} = \frac{H.P. \times 33{,}000}{R.P.M. \times 2\pi} = \frac{H.P. \times 5{,}252}{R.P.M.}.$$

The diameter of the drum is regulated largely by the safe rubbing speed, which should not exceed about a mile a minute. The safe speed in R.P.M. is thus given by

$$\text{Max. R.P.M.} = \frac{20{,}000}{\text{diam. in in.}}.$$

Since this form of braking is brought into action by cutting off the voltage, its effect is not liable to cease through the accidental failure of the supply, the operating of a fuse or circuit breaker, or through a bad or broken connexion. This is therefore the most reliable form of electric brake, and is frequently used as a stand-by when other patterns are in use.

¶ Dynamic Braking.—The principal advantages of the dynamic brake are its strength, its simplicity, and its uniformity. The same addition to the motor is employed for applying it as for obtaining a creeping speed, taking the form of a resistance in parallel with the armature that diverts a certain proportion of the current from it when the line is connected, and forms a load upon the armature when the line is cut off. It is most conveniently applied in an automatic control installation by means of a double-throw pattern of contactor. The connexions are indicated in Fig. 118 A, in which it is shown connecting one end of the armature to the line when the contactor is closed by the coil, and completing the connexion for the braking resistance, while cutting off the

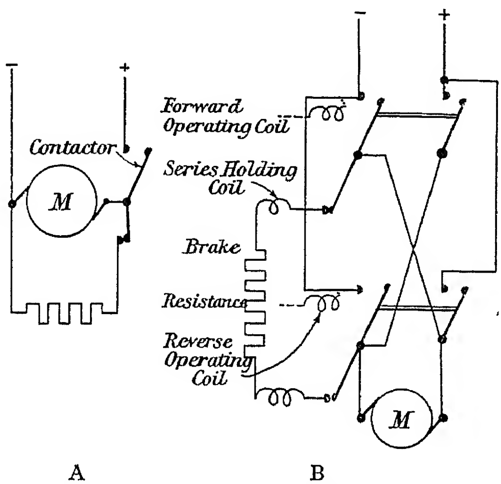



*Fig.* 118. Connexions for dynamic braking contactors.

line, when the contactor armature is released. Since the lower contacts have to carry the whole heavy current from the armature during braking, it is essential that there should be a greater pressure between them than that due to the mere weight of the armature. A series coil is therefore used with most forms of braking contactor, which is energized as soon as the braking current flows, and exerts a strong pull on the armature in this position, forcing the contacts firmly together. The attraction of this series magnet also prevents the contactor from closing while the motor is rotating, even if the normal operating coil is excited, and thus it fulfils a further very useful function as an electrical interlock, preventing the line contact from being made for a reversing installation until the motor has ceased revolving in the original direction. The connexions for a reversing scheme are indicated in Fig. 118 B, in which two pairs of double-pole contactors are shown, each with a single back-contact, the braking resistance being in this case connected between the two lower fixed contact pieces.

A drawback to the simple form of dynamic brake that has been described is that the braking effect ceases if the voltage fails. There are two methods of countering this defect, which will be briefly

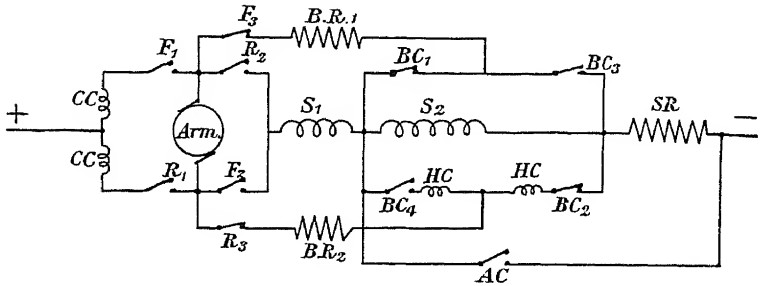



*Fig.* 119. Series field dynamic braking (line diagram).

described here and will be given further consideration in a later chapter. The first method consists of fitting a special series field to the motor, connected by means of a reversing double-pole and double-throw contactor in the appropriate direction for self-exciting the fields for either direction of running; for it will be remembered that a series machine requires the reversal of the field flux when it is changing its function from that of a motor to a generator. This principle is illustrated by the connexion diagrams in Fig. 119, which show the process in the case of a Metropolitan-Vickers planer equipment, there being not only a series stabilizing field *S*1 but also an extra series winding *S*2 controlled by the reversing contactor. The latter requires four separate coils to operate it, two being closing and two holding coils. The second method is to employ a no-volt field switch, which connects the existing shunt field in parallel with the armature if the voltage goes off, thus converting it into a self-excited shunt generator. The connexions for accomplishing this are indicated in Fig. 120.

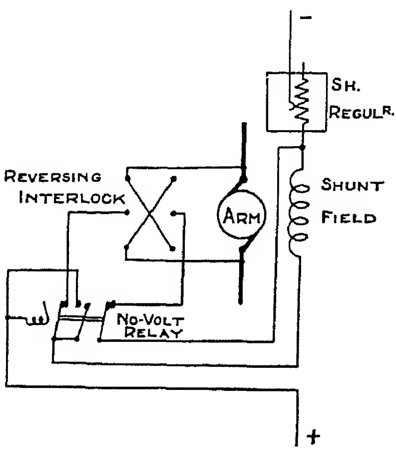



*Fig.* 120. No-volt change-over relay and reversing interlock for maintaining shunt field upon failure of excitation for dynamic braking.

¶ PLUGGING.—It is convenient to refer next to the form of reversal of the functions of the motor known as plugging, which constitutes one

of the most effective means of bringing the armature to rest, especially when the rapid reversal of the rotation is to follow. It consists of the reconnexion of the machine to give reverse running as a motor, and this is accompanied by the simultaneous insertion of resistance in the armature circuit. In the case of a hand-controller the handle would be placed in the first reverse notch, which would reverse the motor in series with all the controlling resistance. With contactors the master controller is simply thrown to the reverse position ; or if there be several speed steps, it may be moved to the first reverse step as in the

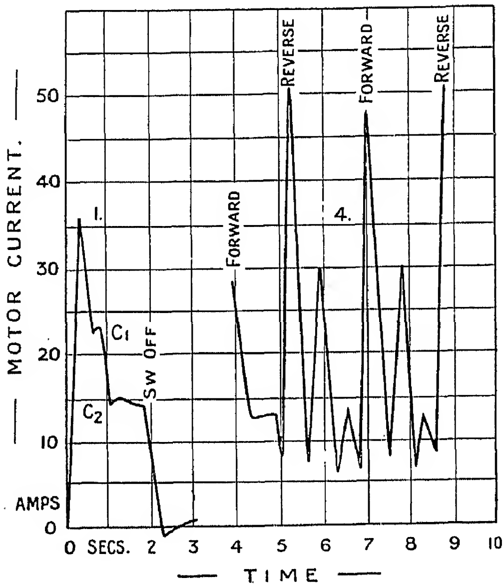



*Fig.* 121. Current peaks during plugging.

case of the manual starter. In the former case the current-limit relays will hold open the accelerating contactors, thus inserting the full contro resistance, which is not cut out until the current falls in the ordinary course as the motor accelerates in the reverse direction.

In applying this method care is necessary that the current peak is not too great for the safety of the motor, and especial attention should be directed to ensuring that the mechanical strength of the winding and the shaft is not overtaxed. It is usually necessary to add extra resistance to that provided for starting in order to keep the current peak within safe limits. In the case of contactor installations, the added resistance is controlled by a preliminary or ' plugging ' contactor, which exactly resembles the accelerating units, and behaves similarly upon reversal. When starting from rest, however, this contactor closes instantly.

This method is especially useful for robust motors connected to loads that require sudden reversal, such as those operating rolling-mill auxiliaries; and also for machines that are commonly reversed at or near the no-load point, such as those operating drilling and tapping machines. Curves taken by means of a recording ammeter showing the fluctuations of current with a 5 H.P. machine of the latter type, when being reversed in this manner, are given in Fig. 121.

It is worth while to consider briefly what happens during plugging, as in spite of the similarity of this procedure to regenerative braking the action is not the same. The net result of reversing the controller is that the motor armature functions in a generating capacity *in series* with the machines in the power station, and the voltages of both combine to force current through the added resistance, which must hence be made high enough to restrict the current to a safe value. It is then the negative torque of generation that constitutes the braking effect, and the fact that a voltage approaching twice that of the line is momentarily applied to the total resistance in circuit enables the magnitude of the plugging resistance to be simply calculated.

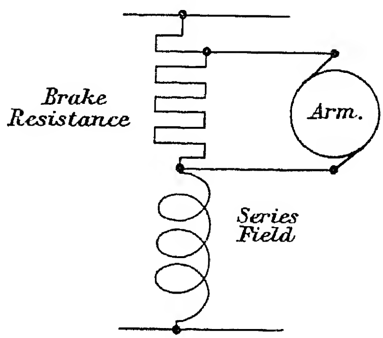



*Fig.* 122. Potentiometer braking.

¶ Regenerative Braking.—Regenerative braking is typically employed to control the speed without bringing about an absolute stop, such as in the lowering of the load on an electric crane. The principle can be most simply explained by reference to A.C. equipment, since it is well known that the induction motor runs normally at slightly below the synchronous speed when developing its normal full horse-power, the slip being then somewhere in the vicinity of 2 or 3 per cent. But if mechanical power is applied while the motor is connected to the supply it now runs as a generator slightly above synchronism, returning power to the line. The great advantage of three-phase electric traction is that the trains are able to descend steep inclines at practically constant speed without any additional brakes other than that inherent in the motor itself, and in so doing they return much of the power to the line that was absorbed in the ascent. In general it is only necessary to leave the motor simply connected to the mains, to enable a heavy load to be lowered with an increase of speed of only a few per cent. over and above normal.

In the case of D.C. plants, the shunt motor travels at almost constant speed whatever the load; and when mechanically driven in the same direction it functions as a generator at a speed which is not greatly increased above normal. Moreover, the speed can be modified as desired by the manipulation of a field rheostat, and thus the rate

not only of lifting but also of lowering can be varied as desired by virtue of the appropriate design of the field circuit.

The same is, however, not true with the series motor, which is characterized by a very variable speed and which rotates in the opposite direction when it is made to act as a generator. Since this form of motor is that most largely used for the hoisting in crane operation, the point is of importance. The difficulty is satisfactorily overcome by converting the winding from series to shunt during lowering. To do this the field coils are connected across the line in series with a resistance. An effective development of the method is shown in Fig. 122, in which the armature is tapped off this resistance in potentiometer fashion, affording an additional means for controlling the speed. The arrangement also lends itself to the change of function, since the modification required in the connexion is a comparatively simple one.

The general scheme that has just been given is the basis of the very valuable form of power-lowering known as 'potentiometer braking'. It is not proposed to proceed to greater detail in the matter at this juncture, as the developments of the method have given rise to somewhat elaborate diagrams that are more appropriately considered in Chap. XX. But the effect of lowering in accordance with this principle can be deduced from what has been said. At each position of the controller the motor lowers the load at a given speed, almost irrespective of the weight. If the load be light, such as an empty hook, then the motor supplies power to overcome the friction of driving it down; while if it be heavy, the machine is driven as a generator, still at practically the same speed, absorbing power.

# XIV

## CONTACTOR INSTALLATIONS

THERE are few diagrams of connexions that appear as complicated at first sight as do those of a contactor installation, and the reading of one representing quite a simple piece of equipment may well move the unversed engineer to despair. The complexity, however, is more apparent than real and will be found to reduce to small proportions when a little experience has shown the right way to go about the interpretation of an existing plan of connexions, and its compilation in the first place. This chapter will therefore be devoted to the process of building up a complete control scheme for carrying out any desired set of functions, and to its expression upon paper.

Like every other difficulty the present one can be readily overcome by splitting the problem up into its constituent parts and dealing with each in detail. This method should be employed first of all in drawing up a control scheme, which is formed by the joining together of elements, each of which will accomplish some item in the requirements. Secondly, the same principle should be borne in mind when the diagram is being compiled, the various portions that go to make up the whole being kept as separate from one another as circumstances will permit. Thirdly, advantage should be taken of the principle when a plan is being interpreted, the endeavour being made to recognize the elements in turn and to segregate them mentally.

The reader will readily appreciate that the clarity of the diagram will be much enhanced if only well-recognized symbols are utilized, as ambiguity will be thereby obviated. The author strongly recommends that the B.E.S.A. standard symbols, as given in British Standard Specification, No. 108, be employed exclusively, as they are clear, definite, easily drawn, and familiar to practically all engineers.

Carrying out the sectionalizing principle, the following list contains the chief individual functions that a contactor equipment may be required to perform :

1. Making and breaking the line connexions.
2. The above, for both forward and reverse running.
3. Acceleration by cutting out steps of resistance.
4. Star-delta acceleration.
5. Auto-transformer acceleration.
6. Speed regulation by cutting in or out field resistance.
7. Speed regulation by shunting the armature.
8. Braking.
9. Inching.
10. Slip regulation of induction motors.

The installation would be made complete by the addition of a suitable master relay or relays, master switch or master controller to give opera-

tion as desired; and also of other relays, interlocks, and auxiliary switches to supplement the control and to safeguard the equipment.

Dealing with the constituent elements in detail, the plain line contactor does not require illustration, as it consists of a simple standard unit for opening and closing the circuit. As with ordinary manual switches the line contactors may be made to operate on one or on both poles in the case of a D.C. installation, the former interrupting the circuit effectively but leaving the apparatus connected to one line; while the latter will effect a complete disconnexion and the apparatus will be dead when the line contactors have opened. Similarly with a three-phase A.C. installation the line contactors may be either two-phase or three-phase, the former leaving one phase connected. In

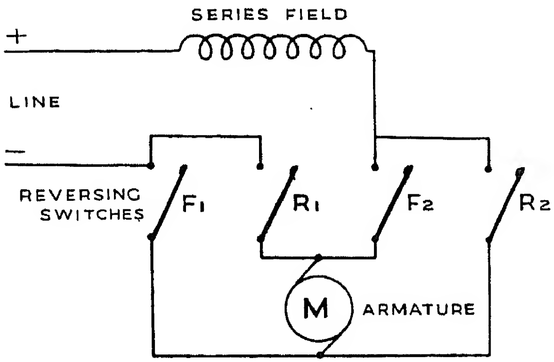



*Fig.* 123. Arrangement of four single-pole switches (or contactors) to effect reversal, e. g. of a series motor.

either case, if the less complete interruption has been adopted, complete isolation is always provided for by means of an ordinary hand switch, which will be double-pole or three-phase as the case may be.

The arrangement of switches for reversing is much more elaborate than in the non-reversing case, as four switch contacts are now required to effect a single-pole reversal with either direct or alternating currents. D.C. reversing switches would be arranged as shown in Fig. 123, where the armature and field of a series motor are shown in position to provide a concrete example. According to this diagram the series field is connected to the positive line, and the armature is connected to the lower contacts of the contactors; so that if *F*1 and *F*2 are closed the current passes downwards through the armature in flowing from positive to negative; while if *R*1 and *R*2 are operated an upward flow is the result, giving the opposite direction of rotation. If it is desired to disconnect the series field, a fifth contactor must be included on that pole; but this arrangement is only used in exceptional cases, as it is undesirable to increase the elaboration of a reversing system still further, and the double-pole knife switch and fuses are relied upon to afford means for

complete disconnexion when needed. The above arrangement might be inverted, by taking the line connexions to the bodies of the contactors, and thus leaving the armatures and moving contacts alive when open. The scheme has, however, an advantage in that adjacent contactors are of the same polarity, and may be interlocked mechanically without the interposition of any insulation.

The A.C. case corresponding to the above is shown in Fig. 124, in which two of the phases going to the stator of the induction motor are interchanged for producing reversal. Since the same A.C. contactor can be made with two or three sets of contacts for the one operating coil, the change from two-phase to three-phase interruption does not involve so great an increase of complexity as with D.C., and it is much more frequently met with than the extra contact in the latter case. It should be noted that in the last two diagrams the exciting coils for the contactors are not shown, for the sake of simplicity.

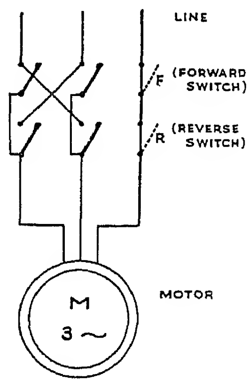



*Fig.* 124. Arrangement of two- or three-phase switches (or contactors) to effect reversal, e. g. of an induction motor.

These line contactors would in practice be provided with interlocks, which would prevent a forward and a reverse unit from being left closed at the same time. There are two possible causes for this mishap, one being a faulty connexion, due to an error in manufacture, a derangement of the master switch, or a short circuit in the wiring; and the other the failure of a contactor to open after the exciting current has been cut off, through sticking either on account of undue friction, residual magnetism in the iron circuit, or 'freezing' of the contacts after a heavy overload. Both figures will show that a dead short circuit would be caused by such an occurrence, and it is therefore prevented by either a mechanical or electrical interlock. The former would not in general be shown on the diagram, and would consist of an attachment between units *F*1 and *R*1, and a similar one between *F*2 and *R*2 in the D.C. case, or between *F* and *R* in the A.C. diagram.

An electrical interlock should follow the same arrangement, and would be shown as an auxiliary contact on each of the line contactors, forming a link in the exciting circuit leading to the corresponding contactor for the opposite direction of running. The ends of the forward and reverse exciting circuits would be connected in the appropriate manner to the master switch, to give the mode of operation desired. Sometimes the coils of both contactors for running in the same direction are connected in series or in parallel, and are protected by an auxiliary interlocking contact on one contactor only for the opposite rotation. This gives incomplete protection, however, for it is now possible for the contactor not fitted with the interlock to stick, and to bring about a short circuit without affecting the protective device. The electrical

interlock for an A.C. contactor equipment needs no comment, as there are only two coils to be considered.

Acceleration is effected by the method indicated in Fig. 125, which is intended to represent the principle for D.C. working, or to form a

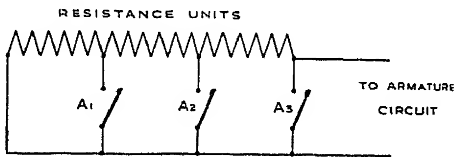



*Fig.* 125. Arrangement of switches (or contactors) for acceleration of motor.

single-line diagram for A.C. working. Three steps of resistance are shown which are short-circuited in turn, beginning at the left-hand end, by the three accelerating contactors, *A*1, *A*2, and *A*3. The open ends are connected in the armature circuit at some convenient place; for example, they may be included next to a line terminal; or they may be connected next to the armature itself, and the current through the resistance thus reversed when the armature is changed over in a reversing

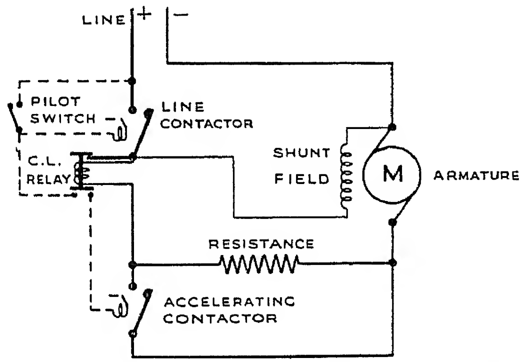



*Fig.* 126. Diagram of simple automatic contactor starter shown in Fig. 127, consisting of one line contactor with current-limit relay, and one accelerating unit.

installation. Again, the contactor coils have been omitted from the diagram for the sake of clearness. All but the last would be connected at one end to an accelerating relay of the type selected; while the other end of all would go to one of the line connexions, these leads being frequently omitted from the diagram and the coil terminals simply marked + or − or *L*, as the case may be, to save unnecessary complexity. For example, if individual current-limit relays are employed with fully automatic acceleration, one relay on a forward line contactor and one on the corresponding reverse unit would have their contacts connected to the coil of the first accelerating contactor *A*1. The relay

contacts associated with the latter would be connected to the coil of $A2$, and so on. The connexions involved for other types of accelerating relay are not difficult to arrive at, and full particulars may be gleaned from the plans of complete installations that follow.

It is now possible to give examples of combinations of the above elements to form diagrams for complete installations. The first, Fig. 126, consists of a simple automatic starting installation for a D.C. motor, there being one line and one accelerating contactor, the actual starter being illustrated in Fig. 127. In this case the line contactor is simply closed by means of the pilot switch, connecting the motor across the line with the accelerating resistance in circuit. The current-limit relay is held up, following the closing of the line contactor and the consequent removal of its mechanical support, by the main current flowing through its series coil; and when this falls to the predetermined value the relay contacts are bridged and the accelerating unit is thus closed. These two elements can be easily separated in the diagram shown, which is perhaps the simplest example of the union of two components of a control scheme.

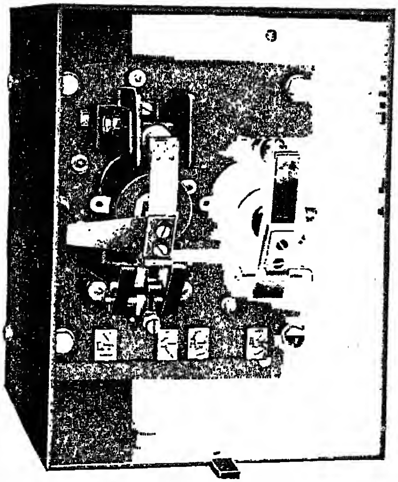


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*Fig.* 127. Small contactor starter.

A more elaborate instance of D.C. motor control is shown in the next diagram, Fig. 128, the actual equipment being illustrated in Fig. 129. In this case the motor is a larger model, demanding five steps of acceleration, and it is also designed for reverse running. It is to be operated by a master switch having two positions, one for each direction of rotation. The latter element is shown on the left of the diagram, and is seen to consist of a single contact drum, one of the fingers making connexion with the positive line while the others connect the latter to the forward or the reverse line contactor coils, depending upon the direction in which the switch has been thrown over.

The line contactors consist of the upper portion of the diagram, and these, together with the connexion to the motor armature, resemble the simple scheme already shown in Fig. 123. In the present case, however, the accelerating relays have been added to the right-hand pair of contactors, while an electrical interlock is shown on the left-hand pair. It has been previously pointed out that the protection afforded by a single electrical interlock is not complete, but the arrangement is used in this illustration for the sake of simplicity. It will be seen that the current-limit relay on either $F2$ or $R2$ will close the

first accelerating unit, the contacts of these relays being connected in parallel.

The accelerating section occupies the lower part of the diagram. It consists of the scheme given in Fig. 125 with the contactor coils and the current-limit relays added, together with their appropriate connexions.

A note should be made with regard to the position of the series coils of the accelerating relays in the diagram. It will be observed that in the case of the accelerating units these coils have been so placed that the closing of a contactor short-circuits the coil of the relay which has

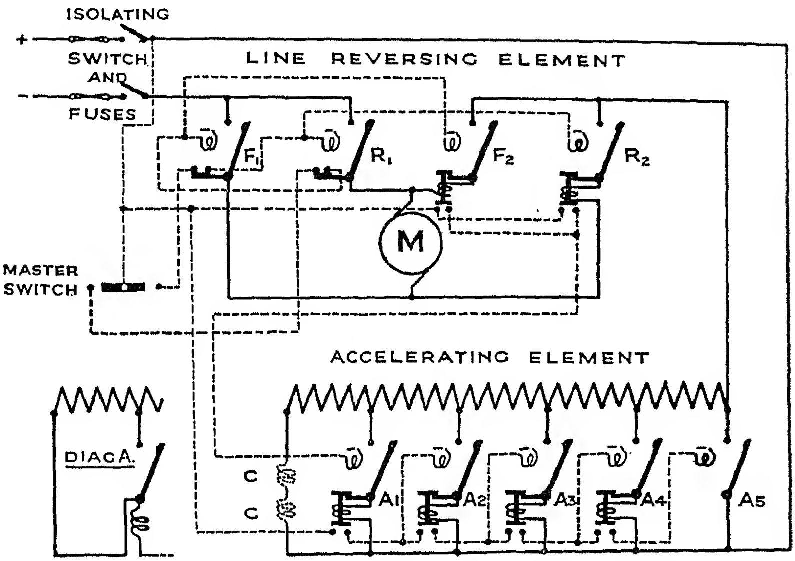


*Fig.* 128. D.C. automatic reversing contactor starter, employing current-limit relays: motor field and its connexions omitted.

brought about its closing, and so renders it impossible for this relay to open again and thus open the contactor in turn. Reopening might otherwise happen, for example, through the occurrence of a sufficiently heavy overload to lift the relay armature; and to guard against such a contingency the rule has been formulated of designing the relays so that they will not be raised by a current less than three times that at which they were released. This condition would be rendered unnecessary if the scheme of connexions to which attention has been drawn were always made. It should be noted that the scheme can be modified, as shown in the small diagram at *A*, by the connexion of the thick lead on the left of each unit to the contactor armature itself, instead of to the series coil of the relay; an arrangement that would usually be more convenient in practice, though it is somewhat more difficult to represent clearly in a full diagram.

Now it will be observed that the relays associated with contactors *F2* and *R2* are not connected in the figure so that they are short-circuited when *A1* closes; and this can be brought about by inserting the relay coils in the position marked dotted at *C*, i.e. in the loop that is short-circuited by the unit *A1*.

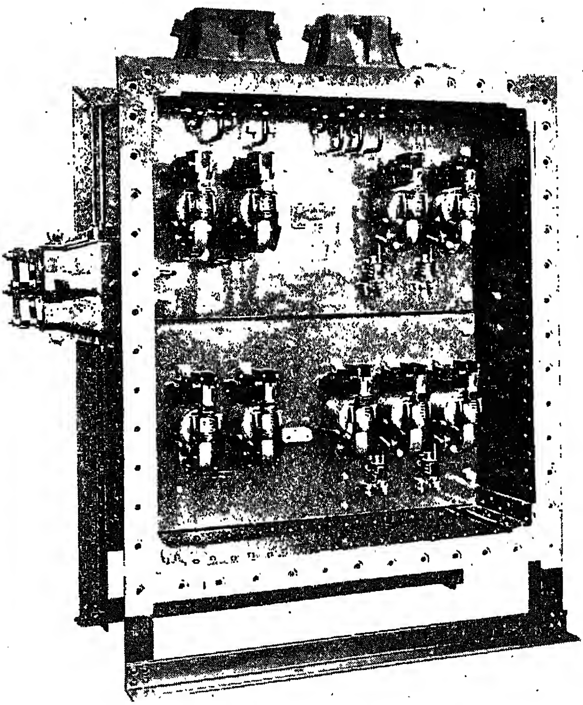

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*Fig.* 129. D.C. reversing contactor equipment for 150 H.P. 500 volts. The apparatus is contained in a flame-proof case and is employed for controlling a mine haulage gear; corresponding with Fig. 128.

Instead of shunt contactors with current-limit relays, series contactors without relays might be substituted. A scheme of connexions for these is given in Fig. 81, Chap. X, in which the contactors close one after the other and are not reopened until the circuit is broken. The last diagram in this chapter, Fig. 142, contains an alternative method employed by the B.T.H., occupying the bottom row of the installation, whereby the contactors drop out again after the short circuit of the resistance has passed beyond them. It will be seen that the resistance

sections are connected alternately in either ' leg ' of the accelerating circuit, and by this means the coils of the previous contactor in each leg are put out of action.

The following installation, Figs. 130 and 131, embodies the control of a large high-voltage A.C. motor, automatically accelerated by means of the separate pattern of relay. Such a motor can be employed (for example) in driving a rolling mill, and it is assumed that reversal of motion is not required. Power is supplied in a typical case at 3,300 volts, and the capacity would be about 400 H.P. There would be

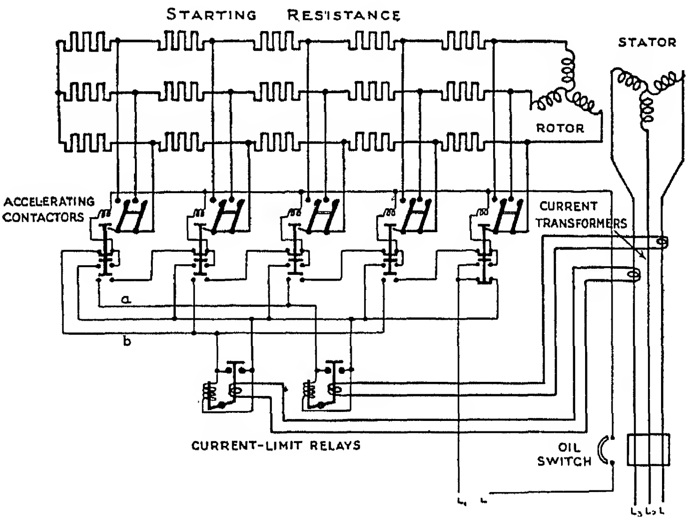


*Fig.* 130. Diagram of contactor equipment for controlling a 400 H.P. slip-ring induction motor, five steps only being shown; view of equipment in Fig. 131.

eight or nine steps of acceleration for this size of motor, but only five are shown, as being sufficient to illustrate the scheme of connexions.

It is a simple matter to keep the line connexions apart from the accelerating portions of the diagram in this instance, since the rotor winding of an induction motor is entirely distinct from the stator, and in the present case the latter is connected to the high-voltage line through a three-phase oil switch. The latter, however, possesses an auxiliary contact which closes the exciting circuit for the accelerating contactors when the stator circuit has been made.

The accelerating system consists of steps of three-phase resistance, which are short-circuited progressively, beginning at the closed end, by means of the appropriate number of double-pole contactors. The function of the latter is to make star connexions right across the three phases of the resistance, two of which are connected to the fixed contacts of the contactors, and the third to the moving contacts, which are

joined together as shown. The coils of all the contactors are connected at one end to the auxiliary contact on the oil switch, and the individual control is effected at the remaining end of each.

A pair of separate accelerating relays is shown in the lower part of the diagram. These are identical with each other, and have their current

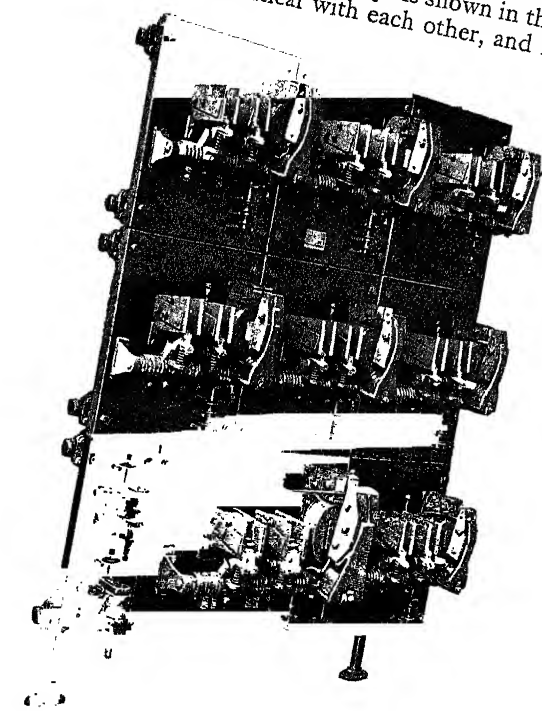

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*Fig.* 131. Contactor equipment for rotor circuit of 400 H.P. induction motor; corresponding to diagram in Fig. 126.

windings supplied from the two outer phases of the stator circuit by means of small current transformers in these phases. Thus the relay contact plungers are always acted upon by currents tending to hold them up and varying in proportion to the load on the stator. The potential winding of each relay is connected across the relay contacts and is joined in series with the coil of the contactor which is about to be closed at any stage, the necessary connexions for bringing these relays into play in turn being made by the auxiliary contacts attached to the armatures of the various contactors.

Three pairs of such auxiliary contacts will be seen below the rocking bars of the contactors. The top pair are connected to the respective

contactor coils, and directly join these in series with the coil of one or other accelerating relay ; but this circuit is not completed, except in the case of the first contactor, until the bottom auxiliary contacts of the preceding unit in the sequence have been joined through the closing of this contactor. The middle pairs of contacts create a holding circuit for the contactor itself as soon as it is closed, rendering it independent of the relays. The excitation is provided for the contactor system generally through the bottom pair of contacts of the last unit in the sequence, which are only closed while this contactor is open. All the

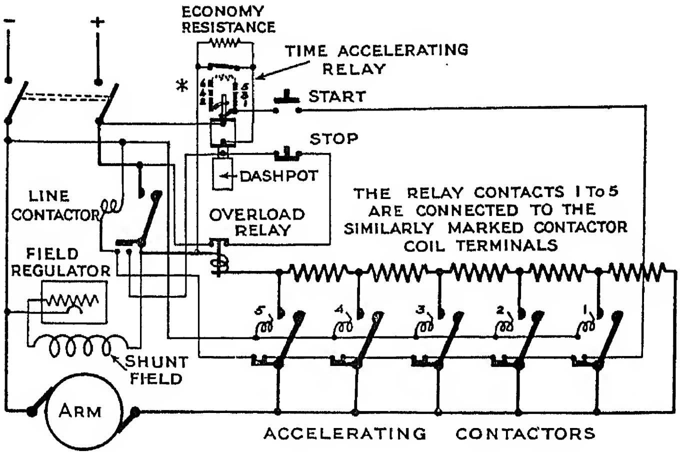


*Fig.* 132. Time-limit contactor diagram with push-button operation, overload protection, and field regulation, for starter panel shown below.

previous contactors, as well as the two relays, are thus de-energized as soon as the resistance is finally short-circuited.

It will be observed that the connexions to the relays are made by means of the horizontal lines in Fig. 130 marked *a* and *b*; and these are tapped alternately for each contactor, throwing the relays into operation in turn.

An example of time-limit control apparatus suitable for the operation of a 150 H.P. D.C. circulating-pump motor is shown in Figs. 132 and 133. The equipment consists of one line contactor, followed by five accelerating contactors, the closing of which is governed by a time-element relay, these elements being easily distinguished. The starting and stopping of the whole installation are accomplished by means of 'on' and 'off' push-buttons, which operate in conjunction with an auxiliary holding contact on the line contactor. An overload relay is connected in series with the 'off' button.

A number of electrical interlocks are involved in the apparatus, of which the most important is that associated with the accelerating contactors. The object of this is to prevent the line unit from closing if any of the others has failed to open. It consists of an auxiliary contact on each accelerating contactor, the former being held closed when the contactor is open. A similar interlock is sometimes added to the line

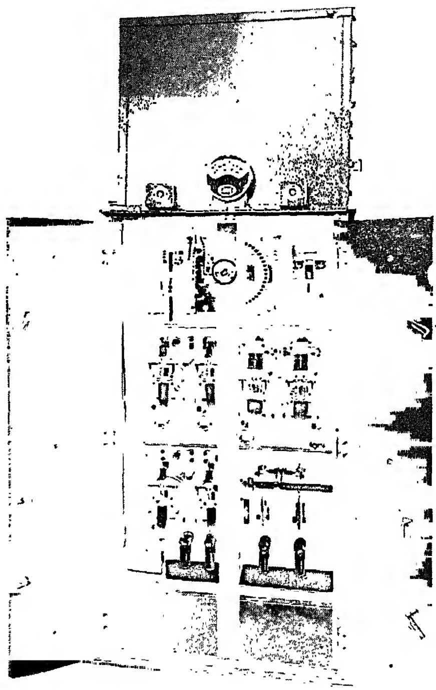

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*Fig.* 133. Time-limit contactor starter panel.

contactor in installations of this kind, in the form of an additional pair of auxiliary contacts through which the exciting current for the accelerating units would be supplied, but only when the line contactor is closed, thus preventing the acceleration from proceeding if the line unit happens to stick in the open position. There is also an auxiliary contact immediately above the time-element relay, which is opened when the plunger of the latter has reached the top of its travel, and which cuts in an economy resistance in series with the relay coil, thus enabling the latter to be overrated. A similar economy resistance can be connected in the coil circuit of the last accelerating contactor by providing an additional contact stud on the relay, as at 6, and by connecting the

resistance between this and the last ordinary stud. In the present instance standard contactors were employed with fully rated coils, and there was thus no need for such an arrangement. Economy resistances are in general to be avoided where possible ; but in such a case as this the means for connecting in the resistance depends upon the normal operation of the relay, and hence an additional set of contacts is not required. The economy arrangement is thus as reliable as the rest of the process.

A feature of this form of acceleration is that the earlier accelerating contactors are opened as soon as the circuit has been made farther along

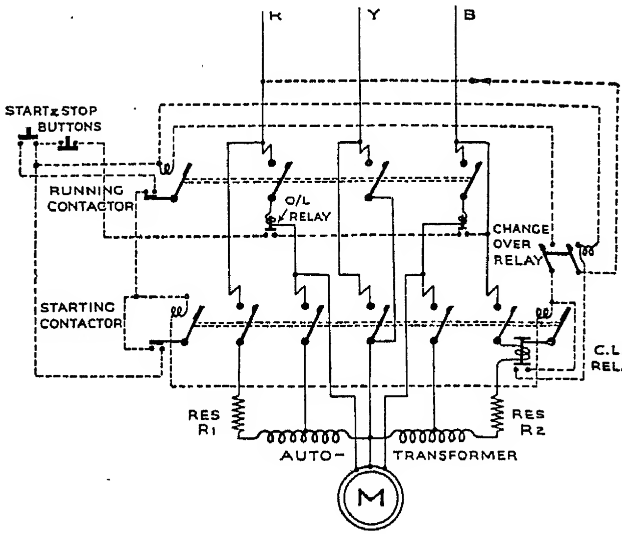



*Fig.* 134. Connexions for auto-transformer starter for 120 H.P. induction motor.

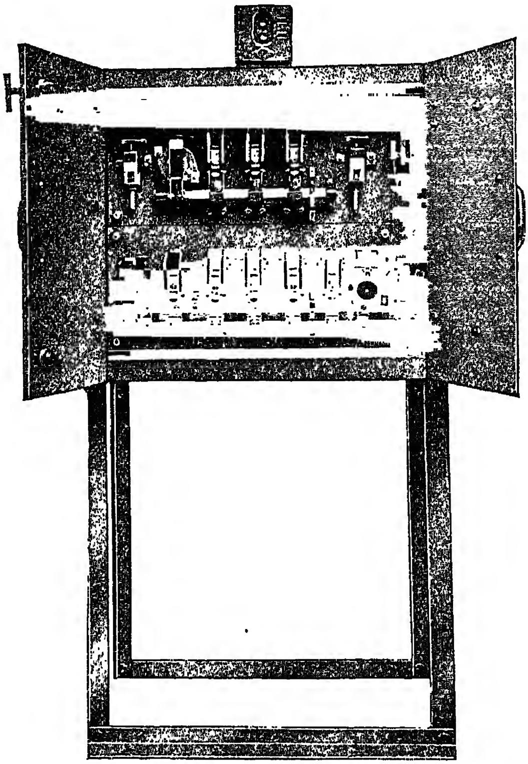


the line by the closing of subsequent units. This economizes in exciting current, and makes it possible to employ overrated coils for all but the last of the accelerating contactors without further elaboration. The form of time-element relay employed here can be made out from the diagram and also from the photograph, consisting of a coil sucking up the plunger against the delay action of an oil dash-pot immediately below, and moving a pair of spring contacts over stationary studs immediately above it. No difficulty will be experienced in compiling an A.C. variant of this diagram.

It will be observed that the speed of the motor is arranged to be controlled by means of a field regulator, exemplifying the sixth function on the preliminary list. In general, a simple electrical interlock is added to compel the short-circuiting of this resistance until full speed has been reached ; or else a vibrating field accelerating relay

is fitted. For the sake of simplicity, however, neither of these has been shown.

The starting of squirrel-cage motors is carried out by means of auto-transformer or star-delta control gear, examples of which are shown in the following figures. A diagram of connexions and a view of an auto-



*General Electric Co., Ltd.*

*Fig.* 135. Auto-transformer contactor starter.

transformer equipment are shown in Figs. 134 and 135 respectively. This scheme consists of two contactors, which may be termed the starting and running line contactors respectively, possessing five and three contacts in the two cases. Except for small apparatus of this type, it is important (as has already been shown in connexion with hand starters on p. 83) that the circuit should not be broken in changing from the starting to the running position, and this also holds good for star-delta units. Accordingly, the lower contactor is first closed, connecting the middle line direct to the middle phase of the motor, and the two outer phases of the line to the ends of the auto-transformer wind-

ings, through resistances $R1$ and $R2$. The second and fourth contacts of the contactor connect the two outer phases of the motor to the tappings on the transformer windings.

When the motor has run up to speed the starting current reduces to a safe predetermined value, and the current-limit relay shown on the right of the starting contactor connects in the small change-over contactor immediately above it. This not only closes the running contactor, but makes its own holding circuit. The closing of the running units opens a pair of electrical contacts shown on the left, which break the exciting circuit of the starting contactor, and this accordingly trips out. For a short period both sets of contacts are closed together, and if it were not for resistances $R1$ and $R2$ the outer portions of the transformer windings would be short-circuited. These resistances are designed to reduce the current that flows during this short interval to a safe value, without themselves overheating.

It will be noticed that push-button control is applied, both the starting contactor and the change-over relay having holding contacts. The five contacts of the lower contactor are operated by two magnets, one at each end of the rocker shaft, having their coils in series. There are two overload relays connected immediately below the outer phases of the running contactor, either of which will open the holding circuit of the change-over relay and so cut off current from the motor.

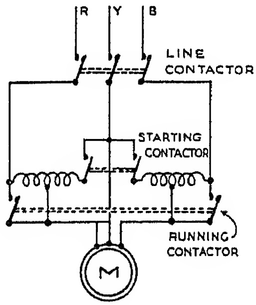


*Fig.* 136. Alternative method of auto-transformer starting.

This control diagram has the advantage that the whole of the equipment is disconnected when the contactors are in the off position. Instead of the current-limit relay a time-limit unit may be substituted, and is, if anything, more suitable than the former, since these motors usually start up at practically no load, and it is therefore in order that the change-over should be effected at the expiration of a given time. The resistances form one of the principal drawbacks of the method, and they are obviated by a slightly different scheme which is indicated in the diagram forming Fig. 136.

In this there are only seven contacts instead of eight, and they are operated in three groups. The first, or line contactor, makes contact from the line to the middle phase of the motor, and also to the outer points of the transformer windings, and this one remains closed for both starting and running. The second is also closed at starting, and connects the inner ends of the transformer windings to the middle line. The third closes the connexion between the motor and the outer points of the transformer coils. When changing over from starting to running contactor 2 is first opened, and 3 is then closed. It will be observed that during the interval between the movements of these two contactors the circuit is not interrupted, but the current for the outer phases of the motor passes momentarily through portions of the transformer wind-

ings, which now function as choking coils. When the third contactor closes, the outer sections of the transformer windings are short-circuited, a proceeding which does not have any ill effect, since they are disconnected at the inner ends. This short transitional period behaves as a small additional step in the acceleration.

Star-delta starting for squirrel-cage motors is a frequent alternative to the auto-transformer method, especially with the smaller sizes. It demands a motor with a slightly specialized stator winding, in that both ends of the phases must be brought out. It has the drawback, as compared with the auto-transformer method, that the starting potential bears a fixed ratio to the final voltage ; whereas with a transformer the initial value can be adjusted at will by moving the tapping-point. It is not possible to arrange for the change-over from the star to the delta connexions without interrupting the circuit, and therefore this method is not used with motors of such a size that an excessive current would be likely to be caused thereby. The limit is in the vicinity of 50 H.P. for contactor equipment.

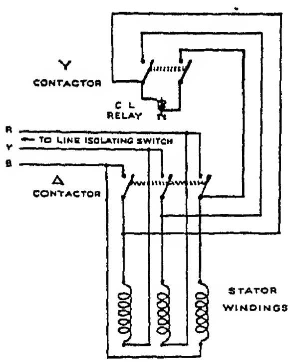



*Fig.* 137. Diagram for star-delta contactor starter.

The contactor gear for star-delta starting is somewhat simpler than in the case of the auto-transformer method, and is indicated in the diagram forming Fig. 137. In this the stator windings are represented by three simple coils, and these are connected to the line through the usual three-phase isolating switch at one end. The three-phase contactor immediately above the windings connects them in delta when closed ; while the two-phase contactor at the top of the diagram connects them in star by simply joining the three ends together. A current-limit relay is conveniently joined between the two phases of the star contactor, and energizes a change-over relay that opens the star contactor and closes that making the delta connexion. As with the auto-transformer starter, a time-element relay can be substituted for this current-limit device and will probably be a slight improvement in most cases. The remaining details, such as the push-buttons, holding contacts, &c., are similar to those employed for the other variety of starter.

Electric braking was dealt with in the last chapter, and its various forms distinguished. No further mention need be made of plugging, since it calls for no addition to the diagram except an extra resistance step, which is cut out immediately when a start is made from rest ; nor of the solenoid type, the application of which is simple and is exemplified in future diagrams. Potentiometer braking is described in detail in connexion with electric cranes (Chap. XX) ; and it is now only necessary to consider the addition of the dynamic type to an installa-

tion. This is illustrated in Fig. 138, in conjunction with the means for obtaining a creeping speed.

Ordinary slow speeds are secured by cutting in the starting or controlling resistance; but for some purposes a very low rate of rotation

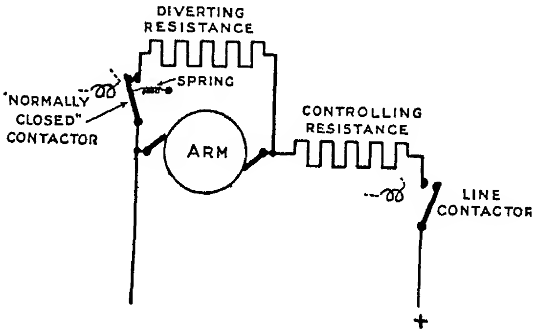



*Fig.* 138. Diagram illustrating the production of dynamic braking and creeping speeds.

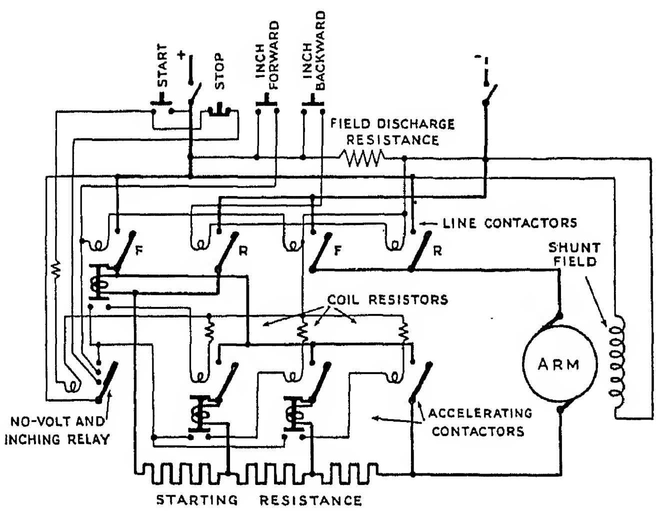



*Fig.* 139. Boring-mill control diagram, including inching and push-button operation and no-volt protection.

is desired, such as for the opening and concluding portions of some types of hoisting. A speed of this description is obtained by diverting a proportion of the armature current through a shunt resistance, as shown in the figure. Here the connexion of the diverting resistance is effected by means of a reversed contactor, which closes its contacts when its exciting circuit is broken.

If the line contactor is opened while the shunt circuit is made, th armature is cut off from the line; but since its terminals are still con nected through a resistance it generates a current which is forcec through this circuit as long as it continues to rotate. This dissipatior of power brings about a powerful negative torque which constitutes ar effective brake. Since the connexions necessary for braking are al brought about by the removal of the voltage, which might be causec by the operation of a fuse or circuit breaker, the dynamic brake i automatically applied under these circumstances. The addition of thi device to an existing diagram presents no difficulties, the chief pre caution needed being the connexion of the field winding (whatever it

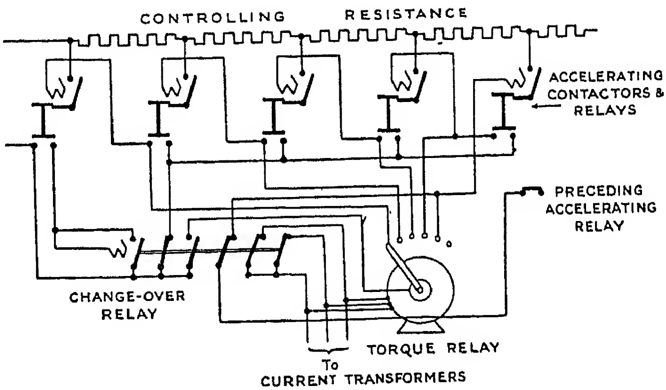



*Fig.* 140. Slip regulator diagram, embodying a torque relay and change-over contactor.

nature) so that failure of voltage does not remove the motor excitatio if braking under no-volt conditions is desired.

There remain two operations in the preliminary list that have nc yet been dealt with, namely, inching and slip regulation. Of these th arrangement employed for inching has been treated in detail i Chap. XII. A normally non-reversing push-button operated equipmer for controlling a boring mill is shown in Fig. 139, inching buttons beir furnished for securing short movements in both the forward and revers directions. There are four line contactors, providing reversal fc inching backwards, and three accelerating contactors. Small resistanc units are shown in series with the coils, a common expedient for avoic ing fine windings, which are apt to be delicate. The connexions for th shunt field are now inserted. On account of the reversing connexior to the armature, a permanent discharge path for the field cannot b provided through the former, and a special circuit with discharg resistance is shown. The forward line contactor alone is equipped wit an accelerating relay, as the mill is only required to rotate continuousl in this direction.

The other example, Fig. 140, shows a portion of the accelerating system of a contactor control gear for a rolling-mill motor, to which has been added the slip regulator occupying the lower half of the diagram. For the 250 H.P. fly-wheel motor employed there would be about eight accelerating contactors altogether, and these would all be closed in succession to start the motor up to full normal speed. When the last has operated, i.e. that on the extreme left, a pair of auxiliary contacts is closed which causes the six-pole change-over relay to function, putting the last five accelerating contactors under the control of the torque relay.

Now the latter consists in this instance of a series-wound squirrel-cage

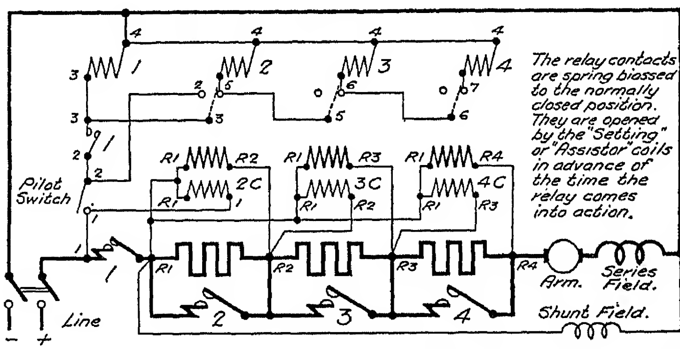



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*Fig.* 141. Diagram of non-reversing starting equipment with pilot switch control and flux-decay current-time-limit acceleration.

motor moving a contact over six stationary studs against the torque of a long helical spring. Current proportional to that in the main motor leads is supplied by current transformers, and makes the contact arm begin to move across as soon as the torque generated exceeds the restraining effect of the spring. Thus the five contactors may be reopened in turn, inserting their resistances into the rotor again, causing the latter to slow down and permitting the fly-wheel to give up energy to assist in overcoming the load peak.

Of the six contacts of the change-over relay, the first is a holding contact enabling the relay to remain closed independently of the auxiliary contacts, and the last two put the torque relay out of action until acceleration has ceased. The third connects the moving contact of this relay to the system, and the second and fourth disconnect the original exciting circuits of the accelerating contactors.

A D.C. non-reversing starter equipment, including combined current-time-limit acceleration upon the flux-decay principle, to which reference was made on p. 158, is illustrated in Fig. 141. In this diagram, which embodies quite an unusual number of windings, the main contacts of the contactors, 1, 2, 3, and 4, are shown apart from the coils

belonging to them, these, however, being given the same numbers. A separate double-coil accelerating relay is associated electrically with each of the accelerating contactors, 2, 3, and 4. The relays are really small normally closed contactors, the coils pulling or holding them open.

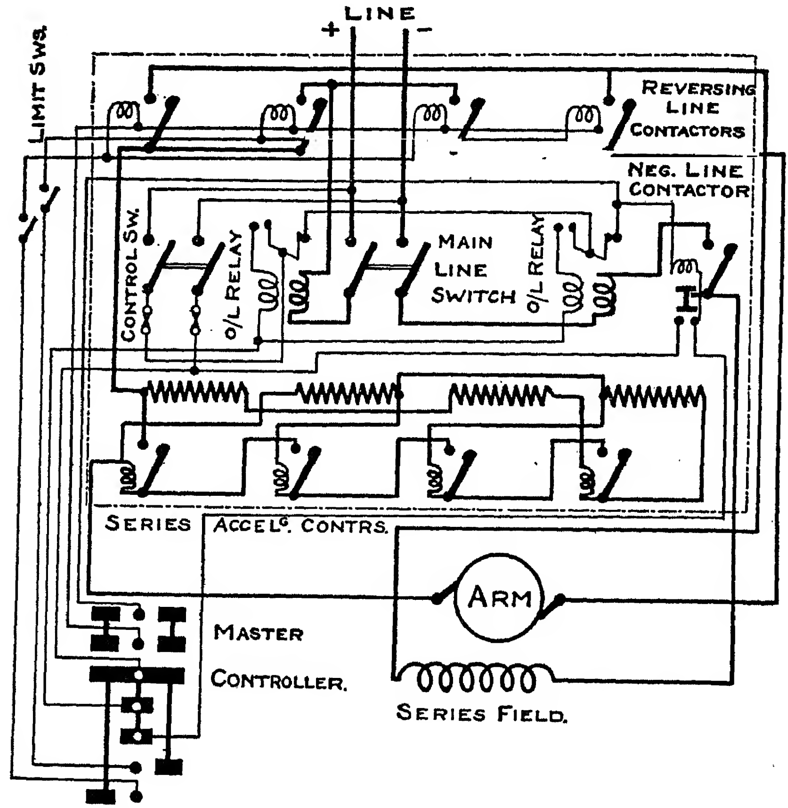



*Fig.* 142. Complete diagram for control of live-roll motor employing series accelerating contactors and electrically reset overload relays.

The lower windings on the relays are the 'setting' or 'assistor' coils, which are connected in parallel with the contacts of the previous contactor. They are thus energized in advance of the closing of the contactor in question, but are short-circuited when closing occurs. Their action is thus first to pull the relay contacts open, and then to release them a definite interval after the previous contactor has closed, the delay being due to the gradual decay of the flux in the short-circuited electro-magnet in each case. The armature is, however, also held open by the upper or current-limit coil, which is connected in parallel with

its own section of starting resistance and its own contactor contacts. It thus carries a current proportional to that in the main circuit until the current peak has descended to the predetermined value, whereupon it releases the relay armature and is itself short-circuited by the closing contactor. The result is that the acceleration is governed by either the current-limit or the time-limit feature, whichever gives the greater delay; and the whole equipment is completely safeguarded from both electrical and mechanical over-stresses.

A number of purely accessory details will be described in conclusion which are not essential to a main scheme, and of which the most important are exemplified in the last illustration, Fig. 142. This scheme has been specially selected for its completeness, and for its inclusion of a number of items that differ from the practice that has characterized the previous examples. It is designed to control a live-roll motor of about 50 H.P. and employs series contactors, to which attention has already been drawn. Partial speeds are, therefore, not obtainable, and the master controller has only one position for 'forward' and one for 'reverse' running. The diagram shows the components all in their actual places upon the panel.

The accessories represented are as follows:

*A. Line Switches.*—These are for isolating the installation when it is desired to carry out adjustments or repairs; and there are two of them, one for the main current and one for the control circuit. This double provision is a convenient arrangement much used for heavy industries, permitting the closing of the contactors and the operation of the relays to be tested without running the motor. Ordinary double-pole knife switches are employed for these.

*B. Cut-outs.*—The main circuit is protected by an electrically reset overload relay on each pole, the shunt resetting coils being connected to a special contact in the master controller which is energized only in the off position. The type of overload relay illustrated makes the circuit for the resetting coil only after it has broken that for all the line contactors, and vice versa. A pair of ordinary enclosed fusible cut-outs are fitted to protect the control circuit.

*C. Extra Line Contactor.*—Although an extra line contactor is not generally employed for ordinary purposes, its use is becoming standard practice for steelworks and mining installations. Not only does this addition open the line circuit on both poles, but it acts as a circuit breaker, being opened as well as the reversing contactors upon the occurrence of an overload, and also for other contingencies if desired. It thus forms an extra safeguard in the event of one of the other units sticking. It is closed by a further special contact in the master controller in the 'off' position only, and thereafter its own holding contacts maintain the excitation.

*D. Limit Switches.*—The object of these being to prevent over-travel in either direction, one is connected in the exciting circuit for each pair of reversing contactors; so that after one has been opened the other reversing units can still close and rotate the motor in the opposite

direction. A reversing master controller such as this, with the same arrangement of limit switches, is often employed for a periodic motion which is not reversing (e.g. that of a tilting mill table or manipulator fingers), identical connexions being taken through the limit switches from the opposite sides of the controller, which is thrown in opposite directions for alternate cycles of operation.

# XV

# MOTOR-GENERATOR CONTROL SYSTEMS AND SLIP REGULATORS

IN the systems of control that have been dealt with hitherto, the necessary circuit modifications have all been effected by the opening and closing of contacts carrying the main current. Although this is not a difficult or even an inconvenient matter when the power dealt with is moderately low, it introduces features that may become troublesome when the size of the motor increases towards the upper limit of, say, 1,000 to 10,000 H.P. and over. For one thing, the carrying and rupturing of the heavy currents required by such large motors form a distinctly more difficult problem than for the more usual capacities. In addition to this the control resistances become very bulky and wasteful of power; while the number of sections, and therefore the complication of the gear, also increases to a serious extent. Even the fluctuations of current and torque produced by the resistance steps become an important matter for very large apparatus, and a smoother method of acceleration is desirable. It has already been shown that the liquid rheostat affords one means for overcoming these defects; but another type of apparatus possessing distinctive advantages is found in the motor-generator, or variable voltage, control system.

¶ THE WARD-LEONARD SCHEME.—There are several variants of this method, the most familiar forms being generally known as the Ward-Leonard and the Ilgner schemes, of which the latter is an extension of the general scheme embodied in the former. Their principle consists of the supply of power to the motor by means of a special generator connected to it by means of leads that are not interrupted throughout the cycle of operations, the control being carried out by the alteration of the generator voltage. Since the latter may be varied by means of a suitable field regulator from a positive maximum through zero to a negative maximum, it will be seen that the motor speed can thus be changed from full forward to full reverse, with any number of intervening graduations, by the manipulation of only the small current taken by the field windings. The switching and control of the heavy current are thus obviated, and large banks of grids done away with.

There is a further considerable advantage, however, in the smoothing away of the voltage and current peaks, which might otherwise have been caused by the steps of the field regulator. This is due to the definite interval taken by the field strength to change its value in either direction, imposing a time-lag in the growth or decay of the voltage and current. If therefore the excitation be changed suddenly by cutting a section of resistance into or out of circuit, the effect on the main current is not abrupt but gradual. Use may be made of this inherent time-element

under favourable conditions to carry out the complete acceleration of the motor by means of the simple switching in of the generator field; but in any case it enables the necessary steps of field resistance to be much reduced in number. On the other hand, the delay may become excessive with big machines, producing sluggishness and necessitating special means for hastening the change of flux.

The complete scheme is given in the diagram forming Fig. 143, in which the motor and generator are simply shown with their brushes joined in parallel. A complete range of excitation, passing evenly through the zero point, is provided for the generator by the reversing potentiometer type of regulator indicated; while the motor is also shown

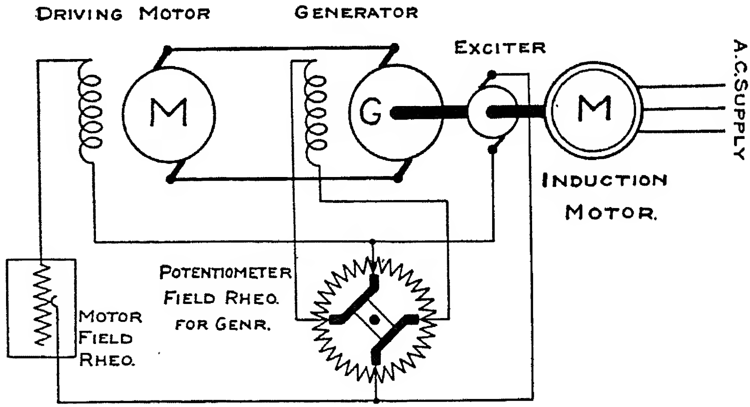


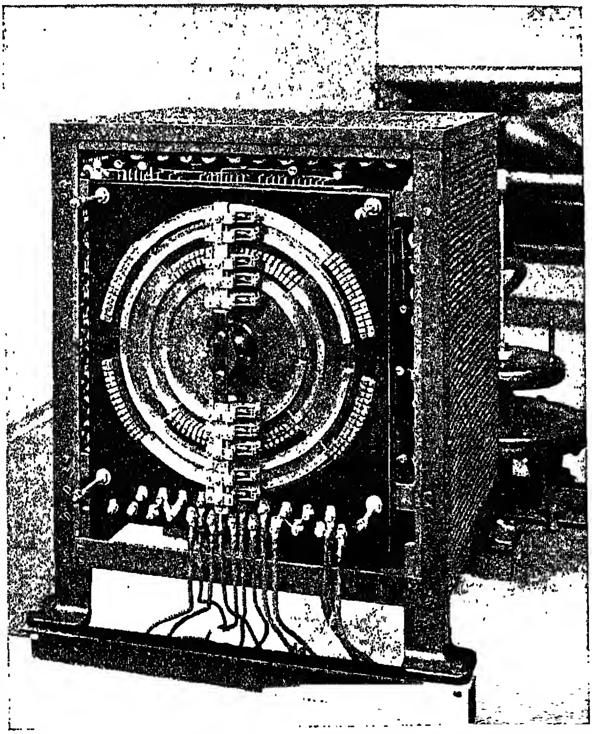

*Fig.* 143. Diagram of Ward-Leonard motor-generator set.

equipped with a field regulator. The latter would be of most use for the quick return motion of a machine tool or similar apparatus, the normal speed of an interpole motor being doubled by this means for light-load portions of the cycle.

Two possible defects of the motor-generator method of control require noting during the course of its design. One has already been indicated, in an excessive time-lag experienced with big machines. When this has to be avoided, the generator field, and frequently also that of the motor, are completely laminated. In extreme cases a special design of exciter, such as that described in connexion with Fig. 165, is employed to expedite the change of flux. The other defect consists of creeping and uncertainty of the driving motor when the regulator is in the neutral position, due to residual magnetism in the generator. The change to the better quality of iron involved in the lamination of the field will also much reduce this effect; but the superposition of an A.C. excitation is sometimes employed to overcome it more completely.

An actual example of a reversing potentiometer regulator is seen in Fig. 144, the cover being removed to show the contacts. It is of course

important to protect the latter from dust and grit, and this is effectively carried out in the English Electric Co.'s design by locating the rheostat itself in the motor-generator room or other enclosed space, and operating it by means of oil-pressure transmission from the control platform, shown in Fig. 145. The back of a rheostat is shown in Fig. 146,



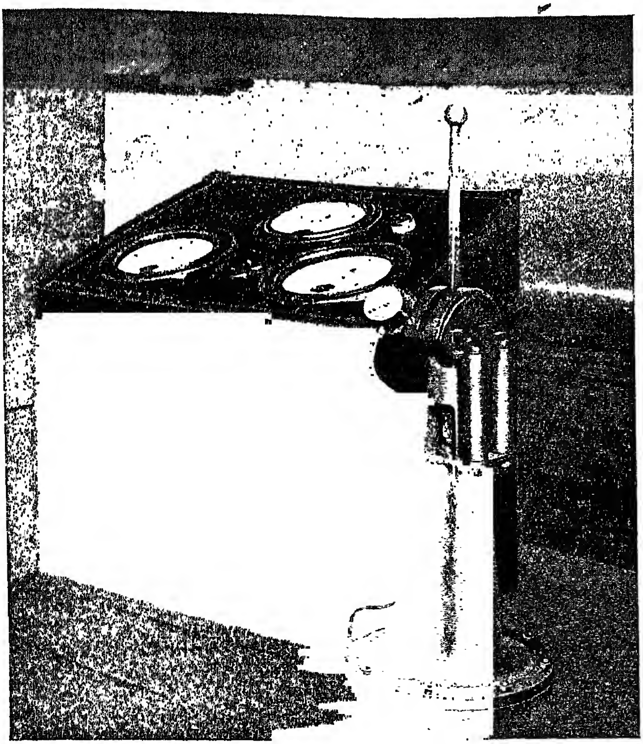
*English Electric Co., Ltd.*

*Fig.* 144. Power-operated reversing potentiometer controller with cover removed from face-plate switch.

together with the oil and air reservoirs, servo-motor (on the left, belted to the fly-wheel set), remote-control diaphragm, and actuating cylinder.

It is not strictly necessary for the generator to be itself driven by a motor; for, although this is nearly always done, it is quite practicable to use an engine for the purpose, or even to belt it to factory shafting It might be thought that when the load runs into thousands of horse-power it would be worth while to derive the mechanical power from a steam turbine; but actually the cost of attendance and the steam-pipe losses are in nearly all cases sufficient to turn the scales heavily in favour of the motor, which is A.C. or D.C. according to the nature of the local supply.

¶ THE ILGNER SCHEME.—The two chief varieties of motor-generator schemes differ according to the speed characteristics of the set. If this is designed to run at constant speed, it is generally called a Ward-Leonard set; and it then functions merely as a rotary transformer, drawing from the line or prime mover the same energy (plus a per-



*English Electric Co., Ltd.*

*Fig.* 145. Instrument desk and driver's lever for power-operated controller.

centage to make good its own losses) that is required by the main motor at any instant. But if the auxiliary motor is designed to run at varying speed, and is equipped with a fly-wheel, it is able, in addition, to store up mechanical energy during the light-load portions of its operation, and give it out again when a current peak occurs. Such an equipment is termed an equalizer or Ilgner set.

The equalizing characteristic is employed widely, not only because it is obtained with but little extra complication, but also because of its great utility. In the first place, it enables a smaller primary motor to be used than would otherwise be the case. It decreases the size of generator that is necessary when two or three such sets are fed from a special generating

station, a condition that frequently occurs in connexion with coal-loading staithes and similar equipment. But its greatest advantage lies in reducing the cost of energy when the supply is drawn from public mains and is charged for on a maximum demand basis. The reduction of peaks also lessens the interference with the supply voltage. A final advantage is the accumulation of sufficient energy to complete a vital operation in the event of failure of voltage. A consideration of these advantages will show when the one or the other variety of equipment is appropriate.

Illustrations of Ward-Leonard and Ilgner motor-generator sets are given later in Figs. 163, 165, 173, 180, 181, 182, and 205.

¶ USE OF FLY-WHEELS.—The accumulation of mechanical energy in a fly-wheel attached or geared directly to the main driving motor is utilized in a number of cases in practice, and these, as well as the Ilgner system, will be considered in this section. The former are not out of place in this chapter, since the principles and the auxiliary control gear are identical for all, and also since the Ilgner set has led the way to the direct application of the fly-wheel in the case of the induction motor.

To begin with, it must be realized that the energy stored in a fly-wheel rotating at constant speed is constant, and that an increase in speed is needed if more is to be accumulated, and a reduction if any is to be given out. Unless, therefore, the motor to which the fly-wheel is attached is designed for variable speed, the stored energy is locked up and the wheel is useless. Suppose, for instance, that a punching machine is driven by a shunt motor and is fitted with a fly-wheel. The theoretical action of the motor is to maintain a constant speed, withdrawing the current from the line necessary to drive any load imposed upon it, however great. Upon this supposition, both motor and fly-wheel rotate idly until the instant when the work has to be done; whereupon the motor maintains the same uniform speed, meeting the whole of the tremendous overload which should have been spread over the revolution as a whole, and prohibiting the fly-wheel from giving up any of its energy. Actually things are not quite so bad, as even the shunt machine is generally subject to a reduction in speed of from 2 to 5 per cent. for large sizes, between no load and full load; and thus a small amount of duty is fulfilled by the fly-wheel. It is obvious, however, that a far greater fluctuation in speed than this is needed. A somewhat similar state of things would hold good for the ordinary induction motor, except that its speed variation is only 2 to 3 per cent., and it has a much smaller overload capacity than the shunt machine.

There are two methods of securing variable speed suitable for fly-wheel purposes, namely, by employing the compound motor for D.C. installations, and the wound-rotor induction machine with slip regulator for A.C. working. The first of these, designed with a 20 per cent. compounding, would suffer a decrease in speed of about 30 per cent. when full load is imposed, a fluctuation that would cause a fly-wheel to give up almost exactly half its stored energy.

The subject of slip regulators will be considered separately.

¶ SLIP REGULATORS.—The induction motor is inherently a constant-speed machine, the reduction between no load and full load being termed the 'slip', and being in the neighbourhood of 2 per cent. for ordinary machines with low-resistance rotors. It may, however, be converted into a variable speed motor by inserting resistance in the rotor circuit, when it behaves similarly to a D.C. shunt machine with resistance in series with the armature. A rheostat employed for the purpose of enabling an induction motor with fly-wheel to slow down on overload is termed a slip regulator.

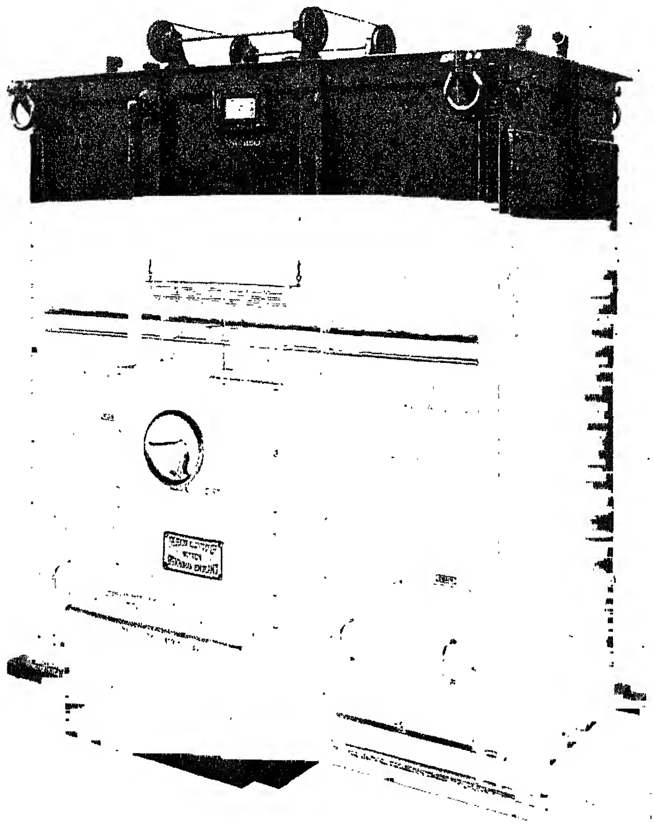
Such a resistance may be employed in two ways. First, it may be included permanently in the rotor circuit, when it constitutes a fixed slip regulator; or, secondly, it may be cut in automatically when full-load torque is exceeded. In the latter case it is generally known as an automatic slip regulator, and may be of the liquid or the solid pattern.

By means of the fixed regulator a speed-torque curve exactly similar to that of the compound motor may be obtained, the speed beginning to fall off as soon as any load is applied. Thus the fly-wheel is caused to give up energy quite automatically; but there is a constant considerable energy loss in the resistance, even when full-load torque is not exceeded. The fixed regulator actually does more than is required or desired, since the motor is capable of operating the load unassisted until full-load torque has been passed. The resistance would be more effectively and much more economically employed if it were cut in after the motor has begun to be overstressed, and were then added progressively according to the demand for more energy.

The latter is the action of the automatic slip regulator, which consists of two main elements, namely, the measuring and motive apparatus, and the variable resistance. Since the former is required to cut in the latter at given values of the current, it will be seen to consist of an ammeter movement on a large scale, the size depending on the force needed to operate the rheostat.

There are two available methods for making an alternating current exert a mechanical force, namely, a solenoid and an induction motor. Of these the first is relatively weak; and suffers from the additional drawback that, unless designed with a very incomplete magnetic circuit, the armature is retained in position by a very much smaller current than was required to pull it towards the magnet. The induction motor, on the other hand, has always the minimum air-gap, and is therefore not only much stronger than the solenoid, but the force developed is always accurately proportional to the current flowing. A squirrel-cage motor with series-wound stator, energized from current transformers with primaries connected in the leads to the main induction motor, is thus employed for the majority of slip regulators. For the liquid pattern, such as that shown in Fig. 145 A, the motor directly raises or lowers the moving electrodes. The moving contacts of a three-phase solid rheostat are moved by a similar device in another design; while the contactor type may have a much smaller torque motor used as a relay to energize the regulating contactors that cut resistance in and

out of circuit. For contactor equipments a solenoid pattern of relay is also employed, one being associated with each regulating contactor, and adjusted to operate at some particular value of the overload current in each case.



*General Electric Co., Ltd.*

*Fig.* 145 A. Liquid slip regulator for 18,000 H.P. (max.) Ilgner set.

The automatic slip regulator must fulfil an important requirement if it is to carry out its appointed functions, and this is that the variation of the resistance must keep pace as exactly as possible with the variation of the current in the main circuit. Since the peaks occur abruptly in the latter, they will infallibly be imposed in spite of the slip regulator if its movement is at all sluggish. Two conditions must be fulfilled to avoid this defect: first, the amount of solid friction must be negligible in comparison with the operating force of the torque motor or solenoid;

and, secondly, there must be no appreciable inertia, which means that the weight of all moving parts must be cut down to the smallest possible limit. Reference to the liquid models used in practice will show how these conditions have been observed, by making the moving arms supporting the dippers of a very light 'lattice girder' construction, and by employing centres or ball bearings for all turning members. The example illustrated in Fig. 145 A employs small pulleys and thin cables in place of arms or levers, the torque motor being housed in a sheet steel case near the floor level. The fluid friction due to the movement of the dippers through the electrolyte is not a drawback unless it is excessive, as it serves to damp the motion and thus prevent hunting.

One necessary feature has not yet been touched upon, namely, the controlling force. It has been mentioned that the slip regulator consists largely of a big-scale ammeter movement, and must thus possess not only the motor element that develops the force, but a spring or weight to oppose the latter and control the movement of the contacts. If a weight is simply lifted in a straight line it requires the same force whatever its position; while the restraining force of a spring is proportional to its extension, and therefore requires a greater force to move it by each successive step.

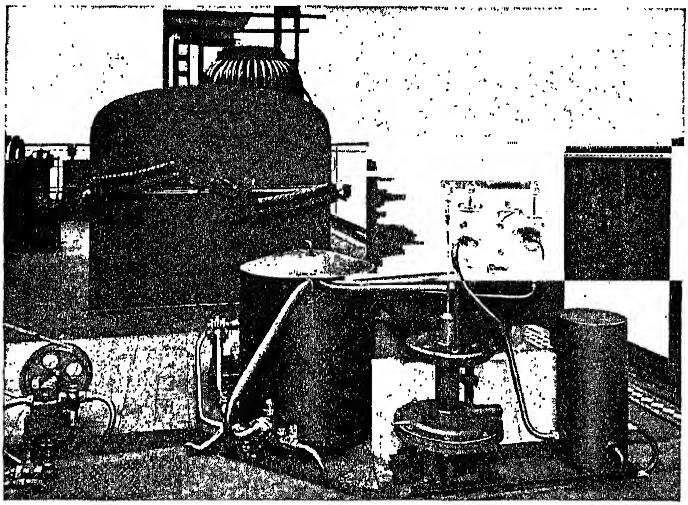
Now it has been shown that the torque motor is required to begin moving as soon as normal load in the main circuit has been exceeded. The simplest arrangement would be for the weight of the dippers and arms to be exactly that needed to counterbalance full-load torque in the torque motor. Usually their weight is somewhat greater than this, and a counterbalance in the shape of a weight or spring is added at the other end of the arm. The former of these possesses the drawback that it increases the inertia of the moving system, while the latter in its usual form progressively increases the force required to lift the electrodes. The latter characteristic, however, may be an advantage.

As an illustration, suppose first that the moving system is weight-controlled. Then, as normal load is exceeded, the dippers begin to rise in the liquid, inserting resistance in the main rotor, which begins to slip. The fly-wheel is thus able to give up some of its energy, and the main current in consequence tends to return to normal. As the current falls, the force exerted by the torque motor also falls, and the movement of the dippers slackens. Normal current in the torque motor will hold the dippers in any position, whereas more will lift them and less will release them; and this state of things permits the fly-wheel to take care of the whole of the overload, the peak being practically removed from the induction motor.

The effect of a spring in place of a weight will be to impose a certain fraction of the overload on the motor, as a greater current than normal is now needed to maintain the deflexion of the torque motor from the position of zero resistance. This sharing of the overload may be desired by the designer, as it may not be practicable to employ a sufficiently heavy fly-wheel to supply the whole peak. A combination of both methods may therefore be selected in order to secure a given operating

characteristic. It should be noted that the spring may be so long that its pull over a short range of movement is sensibly constant, and it thus becomes almost the equivalent of a weight. The spring may also be pivoted to a lever making such an angle with it that the arm reduces as the spring tension increases, and the product of the two is kept constant.

¶ TYPES OF LIQUID SLIP REGULATOR.—There are two forms of liquid rheostat employed as slip regulators, namely, the rotating dipper and the triple-pot types. The latter is perhaps the more common, and



*English Electric Co., Ltd.*

*Fig.* 146. Controller for one of the 14,000 H.P. reversing motors, for the Consett plate rolling-mill, with liquid slip regulator behind.

consists of a tank containing three earthenware or wooden pots with the fixed electrodes at their lower ends, the short-circuited moving electrodes rising and falling through a limited distance above these. Cooling of the electrolyte is effected by means of nests of pipes situated either above or surrounding the pots.

The total amount of resistance to be inserted in the rotor circuit is that required to give the maximum slip decided upon, and the problem is thus not a difficult one, consisting merely of the progressive short-circuiting of the fixed electrodes. It should be noted that the pots, although an important part of the design, are not essential, and means may be found in the future to dispense with them.

Breakage of these, due to unequal heating and mechanical shocks, has occasioned considerable trouble in the past. Wooden pots have given more reliable service ; but in using these it is important that alkaline electrolytes such as washing soda and caustic soda be avoided,

as these effectively dissolve not only the resinous matter in the wood but also any insulating materials with which it may be impregnated. Bicarbonate of soda is used for such rheostats ; but its temperature must be kept comparatively low, or the salt will become converted to the alkaline carbonate.

The revolving dipper type is much simpler than the above, but the location of the cooling coils is somewhat more difficult. Gradual insertion of the dippers is achieved by making them sickle-shaped. They possess relatively little inertia and friction and are not difficult to balance. It is usual to operate them by a comparatively small torque motor coupled to their shaft by means of chains, the gearing enabling the motor to turn through one or two complete revolutions and thus develop more power than if it had only a small angular movement.

An end view of such a slip regulator can be seen on the left of Fig. 146 in which the control springs acting upon the central spindle are clearly seen. In this case the torque motor is directly coupled to the spindle at the other end.

¶ CONTACTOR SLIP REGULATOR.—Turning to the contactor pattern a torque relay designed by the author for governing the operation of five regulating contactors of any amperage is shown in Fig. 104. The motor is of about the standard $\frac{1}{5}$ H.P. size, series wound, and supplied by three standard 40 volt-ampere instrument-type transformers. In addition to revolving the laminated moving contact, it has to move against the pull of a long spring, the tension of which can be easily adjusted, and against the damping effect of an oil dash-pot, which is also adjustable. When used with large contactors of 300 amperes or more, small single-phase auxiliary contactors are connected between the torque relay and the large units, on account of the arcing that might be caused at the brush contact by the very heavy initial current of the big A.C. units, together with the vibration due to their closing. The connexion diagram of such a scheme is shown in Fig. 140.

¶ UTILITY OF THE MOTOR-GENERATOR SYSTEM.—The motor-generator system is used for controlling very large or very fluctuating loads, or for enabling a motor to operate at a wide range of speed, such as 10 : 1. Against its advantages must be set its cost and elaboration, there being now three machines in the place of one, and its low efficiency of only about 50 per cent. for the Ilgner set due to the same cause. About 7·5–10 per cent. out of this would be derived from the slip regulator for the usual range of speed of 15–20 per cent., so that a pure Ward-Leonard plant would show an improved economy to this extent.

As regards the value of the fly-wheel, it is employed when peak loads must be prevented from reaching the line ; and it has certain secondary advantages that have already been enumerated. The expense and loss due to the slip regulator must be balanced against these advantages in deciding for or against its adoption.

¶ CONVERTER FLY-WHEEL SYSTEM.—The advantages of the fly-wheel, without any special starting or speed-regulating characteristics, are sometimes secured by mounting it upon the shaft of a compound-wound motor, which is supplied with power from a rotary converter. An automatic field regulator strengthens the shunt field of the motor when the load is heavy, causing the fly-wheel to give up energy to the line, and vice versa. As the loss due to such regulation is merely that in the field rheostat, it may be regarded as negligible, and this consideration does not limit the permissible speed variation as with the Ilgner set. The machines, as well as the fly-wheel, are therefore much smaller than with the latter for the same service.

# XVI

## ELECTRIC OPERATION OF FACTORIES

IN the days when factories of all descriptions had to rely upon engines for their motive power, the need for constant supervision of the prime mover and the great inefficiency of live steam transmission rendered it necessary to restrict the number of such units as far as possible, and consequently the mechanical power was transmitted to the machines through the medium of great lengths of shafting and belts. To-day, when the electric motor has become the recognized means of operation, the necessity for continual oversight no longer exists, and transmission losses within the factory are practically nil, while the possibility of individual speed control is introduced. Thus the derivation of all the motive power of a large workshop from a single source is no longer necessary; and definite advantages are to be secured, at any rate in many situations, by adopting the opposite policy of providing a separate motor for each machine.

The old method of single-unit drive being now obsolete, there are two alternative schemes available, namely, group drive and individual drive, each of which has characteristics fitting it for certain situations. The former is naturally a constant-speed arrangement, and makes the simplest of demands on the control gear; but the latter opens the way for specialized automatic control, effecting great improvements in the output and general efficiency of the driven machine. It is the purpose of this chapter to deal with the control of group drive, and with the simplest forms of individual operation, as applicable to factories generally, leaving the more elaborate special cases to be dealt with in Chaps. XVIII to XXII.

It may not be out of place to summarize briefly the principal advantages of the electric drive, as this will enable the gain to be estimated that may be effected by subdivision of the power unit. An analysis of the position is of especial value, as present-day practice is undoubtedly backward in taking full advantage of the new order of things; and this is chiefly due to an imperfect realization of the additional possibilities afforded by electrification, which are briefly as follows:

(1) The expense of providing and operating an engine-room is obviated. By means of the capital that would have been expended in this manner, the factory plant itself may be extended and its earning power increased. The saving in attendance, fuel, &c., is balanced against the cost of an electricity supply.

(2) The use of belts and line shafting is decreased or abolished, greatly reducing the losses in transmission to the various machines, giving a less fluctuating speed, and bringing about very important improvements in factory conditions.

(3) The effects of a break-down in the motive power or in an important link in the transmission are greatly restricted.

(4) The flexibility and convenience of the electric motor as regards operation and control are great as compared with the older sources of power.

It will be observed that at any rate a certain amount of subdivision is presupposed in the second of the above clauses, and as a matter of fact this is always practised ; for no factory containing more than about a dozen machines would draw all its power from a single motor. Thus the individual advantages that are derived from the removal of belts and shafting are of general interest, and are well worth considering in detail. Of these, economy in power cost is mentioned last, as it deserves numerical treatment.

(*a*) The absence of belts, pulleys, shafts, bearings, &c., filling the overhead space, brings about an enormous improvement as regards the amenities of the factory. It becomes cleaner and more healthy. Its chief sources of danger to life and limb are abolished. The very serious interference with light caused by the overhead gear is removed, resulting incidentally in a higher standard of workmanship.

(*b*) The effects of periodical belt troubles are obviated, as well as the cost of maintenance.

(*c*) The factory building need not be designed to withstand the stresses of mechanical transmission, and may therefore be considerably cheapened.

(*d*) Overhead cranes can be freely employed wherever heavy work has to be handled, without special arrangements for securing head room.

(*e*) With individual drive there is complete freedom as to the location and arrangement of the machines. Their position may be changed with the greatest ease, as may be rendered advisable, for example, by a change of process.

(*f*) Individual drive renders available a greater amount of power at the machines and a greater overload capacity than is possible with group drive. Fly-wheel operation may be employed for fluctuating loads.

(*g*) It is possible with individual drive to secure the closest and most constant speed regulation for every machine, and thus to work all at their highest efficiency.

(*h*) Variable speed may be obtained in any number of steps by the field adjustment of the individual motor with greater ease and exactness than is possible by mechanical means.

(*j*) There is perfect facility for the running of individually driven machines during overtime, &c.

(*k*) Individual drive does away with the special difficulties of line shafting in concrete buildings.

(*l*) The wastage of power in belts and shafting is avoided. So great is the saving on this account that it will be of interest to make the actual calculation, based upon the figures and investigations of Lozier.[1]

It may be taken as a general rule that if a belt-driven machine shop

[1] See 'The Operation of Machine Shops by Individual Electric Motors', *Journal A.I.E.E.*, vol. 20, p. 115, 1902.

is equipped with apparatus demanding, say, 100 H.P., then at least another 100 H.P. will be absorbed in the belts and shafting, quite irrespective of the number of tools in use. Now it has been found that the average load factor of a machine shop is 30 per cent., i. e. there is on an average just under one-third of the maximum power demanded at any one time. Thus the efficiency of the power transmission works out at as little as 23 per cent. It should be noted that these figures apply to a well-ordered installation, and that far greater losses are possible and have been experienced where the design and maintenance have been defective.

It is possible to supply a fairly close average relationship for the cost of the power required, giving the following transmission costs for the three cases, expressed as percentages of the cost of the product:

| | |
|---|---|
| Steam-engine with shaft and belt transmission . | 2 per cent. |
| Motor group drive . . . . . . | 1 ,, |
| Individual motor drive . . . . . | 0·4 ,, |

A certain amount of belt loss between the individual motor and the machine is assumed in the above, a factor which is now disappearing in consequence of the improved design of the machines themselves.

In order that the magnitude of these losses may be better realized, a concrete instance is worked out below in the shape of a plant with an output valued at £100,000 per annum.

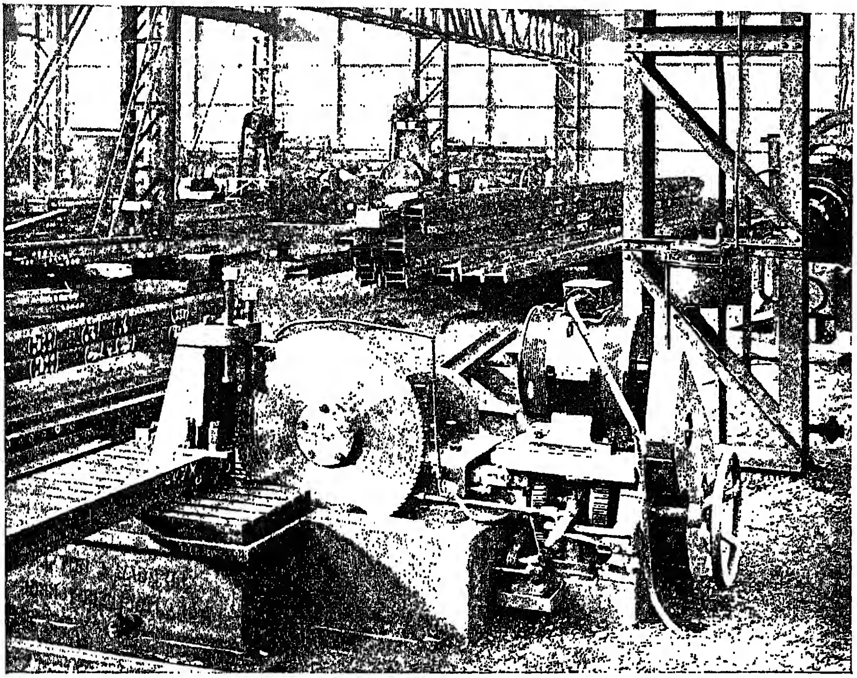
| *Type of Drive.* | *Power Cost.* | *Annual Saving.* |
|---|---|---|
| | £ | £ |
| Belts and shafting . . . | 1,700 | — |
| Motor group drive . . . | 850 | 850 |
| Motor individual drive . . | 400 | 1,300 |

It will therefore be seen that the relative saving in running cost by the omission of the belts and shafting is far from being negligible.

The aim in the adoption of electric drive should be to utilize the peculiar advantages of electricity to the full, by designing the plant so that the inherent drawbacks of the older state of things are avoided as completely as possible. It is also important that no new defects are introduced, and this can only be secured by care in the design, protection, and location of the electrical apparatus. Security will thus be conferred against break-down through mechanical weakness of the apparatus itself, lack of skill on the part of the operator, or unfavourable conditions such as damp or dirt; and against electrical dangers to the workpeople and building. The following rules should therefore be observed:

(1) The size of the groups should be kept as small as possible. There are many practical authorities who maintain that individual drive is preferable in every case, even with the smallest machines; and there are numerous engineering and other factories that employ the principle to the fullest extent and apparently with complete success. Without necessarily endorsing this claim, the author has no hesitation in urging that belts and shafting be avoided as far as is considered practicable.

(2) The motors should be located in positions where they are out of harm's way and do not monopolize valuable space. If they are required to drive single machines they should be mounted for preference upon the machines themselves, as exemplified in Fig. 147; and in the process of time, when the machine makers have become more familiar with electric drive, the design will provide for the reception of a motor



*English Electric Co., Ltd.*

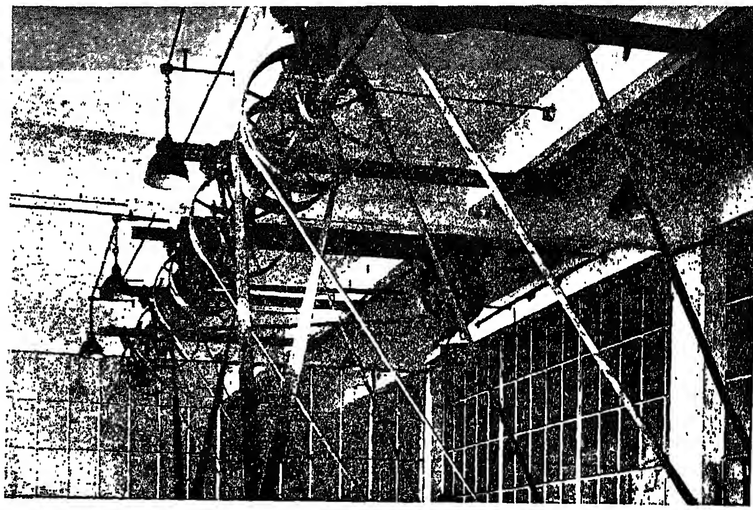
*Fig.* 147. Cold saw in the structural steelworks of Messrs. Sir William Arrol (Swansea), Ltd., with squirrel-cage motor drive and star-delta starter.

as a matter of course, a practice that is as yet far from general. Things being as they are, it is often necessary to find as convenient a place as possible upon the floor close to the driven machine; or if line shafting has to be rotated, the ceiling or walls form a more suitable situation. All modern factory buildings that are intended to house group-driven machinery have slots incorporated in the structure through which bolts may be passed for clamping motors, as well as the overhead gear generally, to walls and ceiling. In Fig. 148 may be seen a ferro-concrete building in which T-slots are cast in pillars and walls, as well as in the ceilings.

(3) The location of the control gear is even more important than that of the motors; for whereas the latter need only be accessible to the

maintenance men for very infrequent attention, the starters, controllers, and regulators must be placed where they can be manipulated as required, without involving loss of time or undue inconvenience on the part of the operator. In addition to this, they must, like the motors, be in safe situations where they do not use up valuable space, as in Fig. 147.

(4) The electrical equipment as a whole, and especially the control gear, should be so designed that it requires no additional care or trouble



*General Electric Co., Ltd.*

*Fig.* 148. Ceiling of ferro-concrete building, showing T-slots cast in to facilitate installation of motors, control gear, shafting, &c.

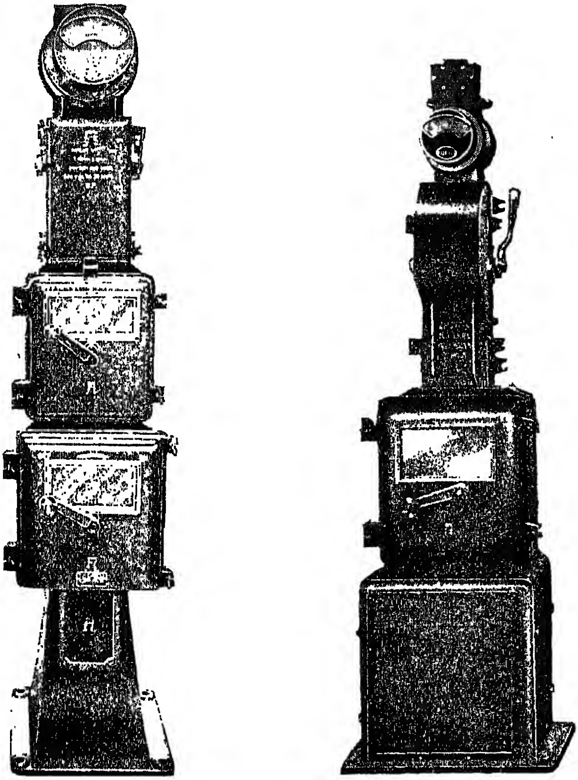
as compared with all-mechanical drive, apart from the services of a special maintenance man for a large number of machines.

¶ Motors for Line Shafting.—The selection of the correct type of motor for operating line shafting is a simple matter. In the first place, constant speed is required; and in the second, the working load is disconnected for starting. For D.C. working, therefore, the shunt motor is definitely indicated; and for A.C. the squirrel-cage induction machine with star-delta starter for units up to about 30 H.P. (which should include the great majority), and auto-transformer or rheostatic starters for larger capacities. The author has known compound motors employed for this purpose, a practice that is obviously wrong, as the speed of the driven machines is thus made to vary according to the number connected.

When there is a choice of system, the A.C. motors should be preferred as being the smaller, cheaper, simpler, and more robust. The conversion of an incoming A.C. supply to D.C. for operating line shafting

is decidedly a step in the wrong direction, in spite of the recent examples of such practice that are to be met with.

Occasionally very large A.C. drives, such as 700 H.P., are effected by single slip-ring induction motors, operated by means of an oil switch



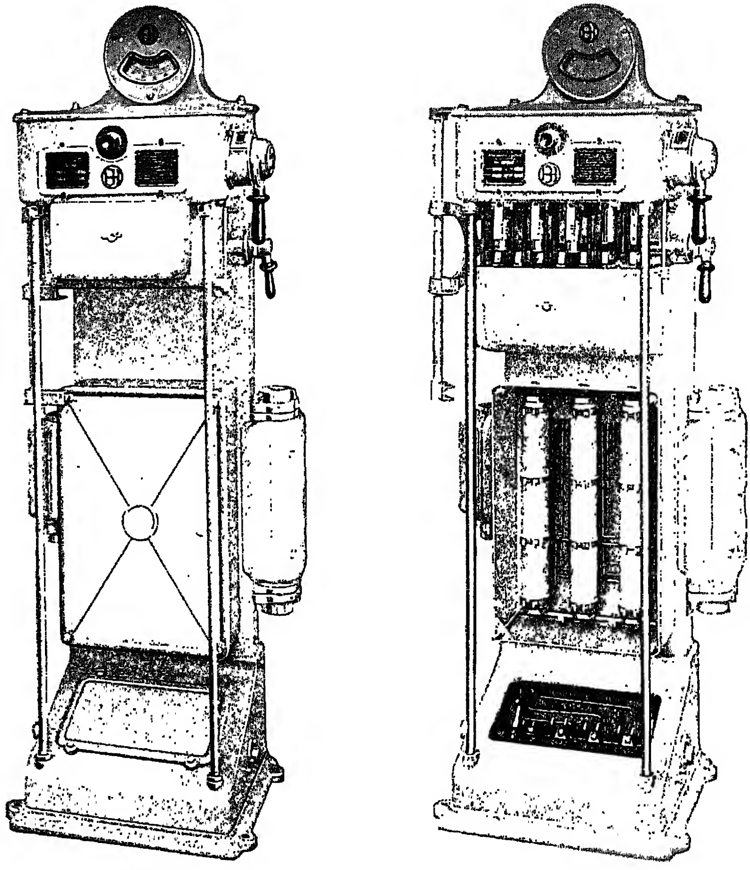
*General Electric Co., Ltd.*

*Fig.* 149. Built-up ironclad control pedestals.

in the stator circuit and a drum starter in that of the rotor. Self-starting synchronous motors are also sometimes employed, where the rectification of power factor or extreme constancy of speed is of importance.

¶ CONTROL GEAR FOR LINE SHAFTING.—Since no speed adjustment is needed in connexion with line shafting, the requisite control gear is narrowed down to starters, together with the associated switches and cut-outs. Two principal characteristics are demanded, in that they must be ironclad and robust. The former affords the full measure of protection required in such a situation, while the latter provides

against the rough and possibly unskilful handling that at times characterizes machine shops. The use of ' mistake-proof ' apparatus, such as time-interlocks for A.C. control gear and inching starters, confers a real advantage.



A B

*Brookhirst, Ltd.*

*Fig.* 150. Rotor control pillar. A, closed. B, open.

There are a number of fully developed and reasonably cheap ironclad types of starting equipment on the market, and one or other of these should certainly be employed. The separate items may be affixed to a wall or column conveniently near the motor ; but it is often possible to find floor room for the neater and more convenient pedestal or pillar form of switching equipment, examples of which are shown in Figs. 149

and 150. In the former the separate pieces of ironclad apparatus are combined to form a 'control pillar', which may be further extended into an ironclad 'switchboard' for the control of more than one motor, on the 'expanding bookcase' principle. There are only two units necessary per motor, namely, the switch and fuses contained in the one casing and the starter in the other. An ammeter, and also a voltmeter if desired, would be added at the top in a separate fitting; while when two more units are joined to form a 'board', a busbar chamber is attached to the top, which may be designed to hold the meters in addition.

The Brookhirst pillar shown in the second illustration is a self-contained unit, comprising all the required equipment conveniently housed in a single sheet-steel assembly case. This particular example is intended for the control of a large slip-ring induction motor, and is shown both closed and also with oil tank lowered and covers removed, exposing the contacts, resistors, and connexions. At the top is the ammeter in a cast-iron hood, while immediately below are the rotor starter and triple-pole stator circuit-breaker, both oil-immersed, contained in the same case, and actuated by the same handle; though the breaker can trip independently of the latter upon overload. There is also a triple-pole isolating switch in a separate sealed chamber, interlocked with the breaker so that the circuit must be made and broken under oil.

The single operating handle works upon the ratchet principle, giving a slow-motion 'step-by-step' movement to the starter. Once begun, the starting motion must be carried out in the correct sequence and completed, otherwise the breaker is tripped. The tank is also interlocked so that it cannot be lowered unless the isolator is first opened.

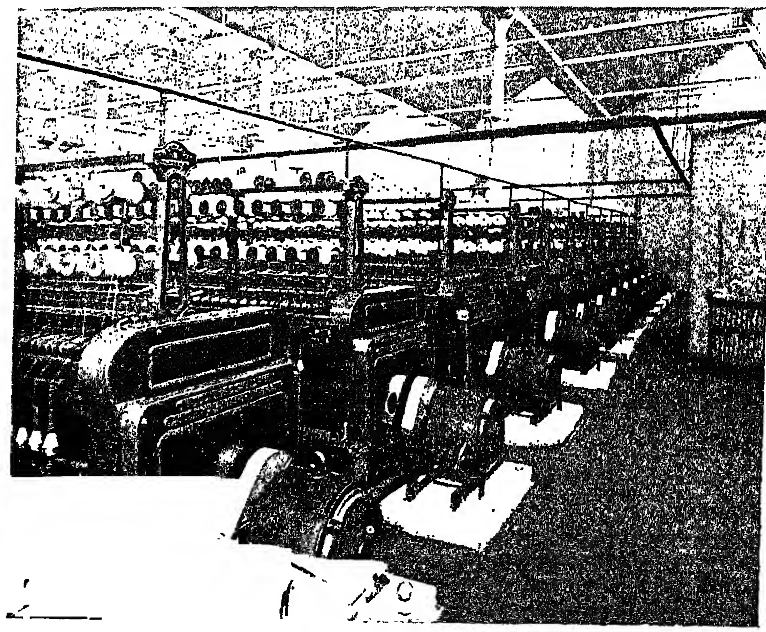
¶ THE DRIVE OF TEXTILE FACTORIES.—The special case of the textile factory may be considered in some detail, partly as an illustration of what has already been stated and partly because extra precautions are needed when such a mill is to be driven. Not only are both group and individual drive included, but the operations are in general so sensitive as to exemplify in a striking manner the problems involved.

There are two features to which particular attention has to be devoted in these mills. The first is the great uniformity of speed required to ensure continuity of running and a high rate of output, and the second is the scrupulous cleanliness needed throughout most of the process, especially as regards matter deposited from above.

Constant speed is essential for two reasons. Most of the machinery is employed in treating the wool or cotton fibres in such a way that the faster the work is performed the greater the tensile stress that is applied to them. A breakage holds up the work and wastes valuable time; so that if delays on this account are to be reduced to a minimum, and a high rate of output maintained, there must be no fluctuations exceeding about 3 or 4 per cent. of normal speed. The looms, on the other hand, are percussion apparatus, the threads being passed through the fabric

in shuttles that are propelled by means of blows from the 'picking-sticks'. Unless just the right velocity is attained by the shuttles, they either do not complete their travel correctly or else they rebound, in both cases holding up the work.

The old method of driving textile factories consisted of locating a steam-engine in the basement somewhere near the centre of the floor area and transmitting the motion to the machines on the various floors



*General Electric Co., Ltd.*

*Fig.* 151. Textile mill, showing motors and control gear.

by ropes or belting. Now there is no difficulty in regulating the speed of the engine to within 3 per cent., but unfortunately the mechanical transmission is responsible for fluctuations at the machine pulleys that frequently reach 15 or 20 per cent., chiefly due to rope slip.

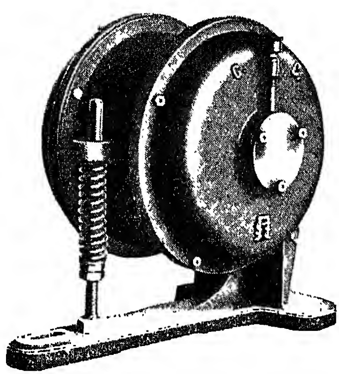
Since the process of spinning and weaving consists in the twisting together and interlacing of strands to form a fabric, any foreign matter that may fall upon this while in the process of formation becomes incorporated and causes imperfections that reduce the value of the product, the depreciation being the more serious as the texture becomes finer. Thus the use of belting, which is liable to scatter such flecks and particles besides raising dust and distributing oil from the bearings, should be limited to the smallest practicable amount.

It will be readily seen that both these considerations favour individual

drive, which is now actually used to a greater extent in textile mills than in any other type of factory, in spite of the small horse-power required by many of the machines. There is, however, yet another factor which tends in the same direction, namely, the requirement in the case of ring-spinning frames of a gradually changing speed as the operation proceeds, the duration of each cycle being about 15 minutes. By using an adjustable speed motor to each frame the output can be increased by about 15 per cent. as compared with constant-speed conditions.

A typical example of textile factory drive is shown in Fig. 151, where a row of doubling frames are driven by $7\frac{1}{2}$ H.P. motors with drum-type starters.

¶ Textile Motors.—The most usual motor employed for the majority of textile machines is of the squirrel-cage induction type; though, if the power supply is in the form of direct current, shunt or counter-compound motors may be employed, with proper safeguards. There is no doubt, however, that they are inferior to the induction machines, for several reasons apart from those already given as holding for factories generally. Not only is their speed less constant over short periods of a few seconds, but the gradual increase due to the heating of the shunt-field winding is sufficient to constitute an appreciable defect. The atmosphere in a textile mill is kept humid, and it is frequently hot, especially near the ceiling; while cotton dust floating in the air of some rooms would be liable to cause commutator troubles. The greater robustness of the squirrel-cage motor, therefore, weighs even more heavily than usual in its favour in these places.



*General Electric Co., Ltd.*

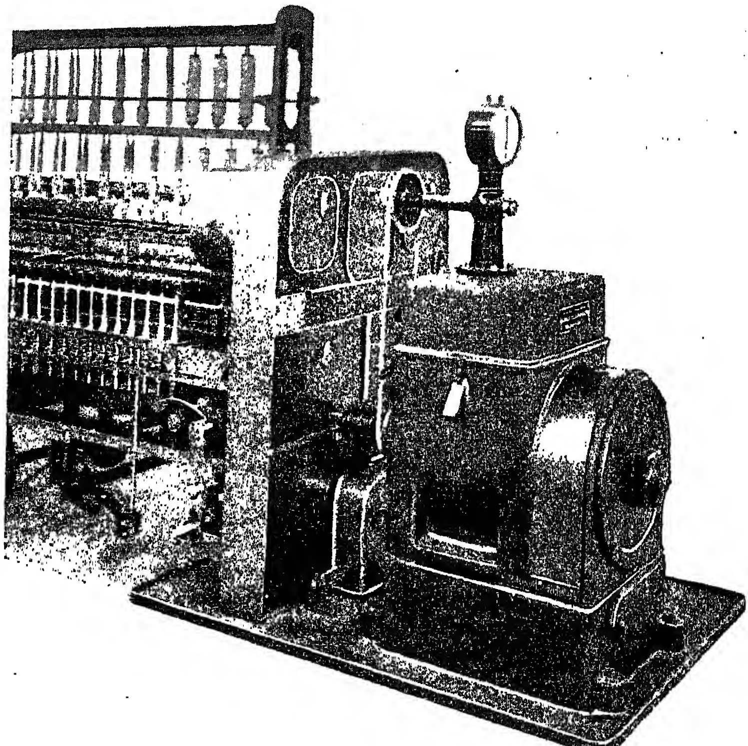
*Fig.* 152. Loom motor.

The use of individual drive for low horse-power machines has resulted in the production of special small 'loom' motors of 0·5, 0·75, and 1 H.P., an example of which is shown in Fig. 152.

There are, however, two other A.C. motors that may also be employed for certain purposes. One of these is the synchronous machine, the use of which may be worth while in place of the larger capacities of induction motor, on account of its absolute constancy of speed and its capability of correcting a lagging power factor. Since nearly all textile drives incorporate a friction clutch for gradual starting purposes and for bringing about somewhat frequent stops, a high starting torque is not required.

The other type is the single-phase repulsion or polyphase commutator motor, which is successfully utilized by several manufacturers for giving the adjustable speed needed for ring-spinning. As it is only

necessary to move the brushes in order to change the speed, the control is simple, and is actually effected automatically in one design by connecting the brush rocker to a bar resting on the 'cop' of the yarn, moving as the diameter of the latter alters. According to another method, the rocker is adjusted by a steel tape passing over pulleys on



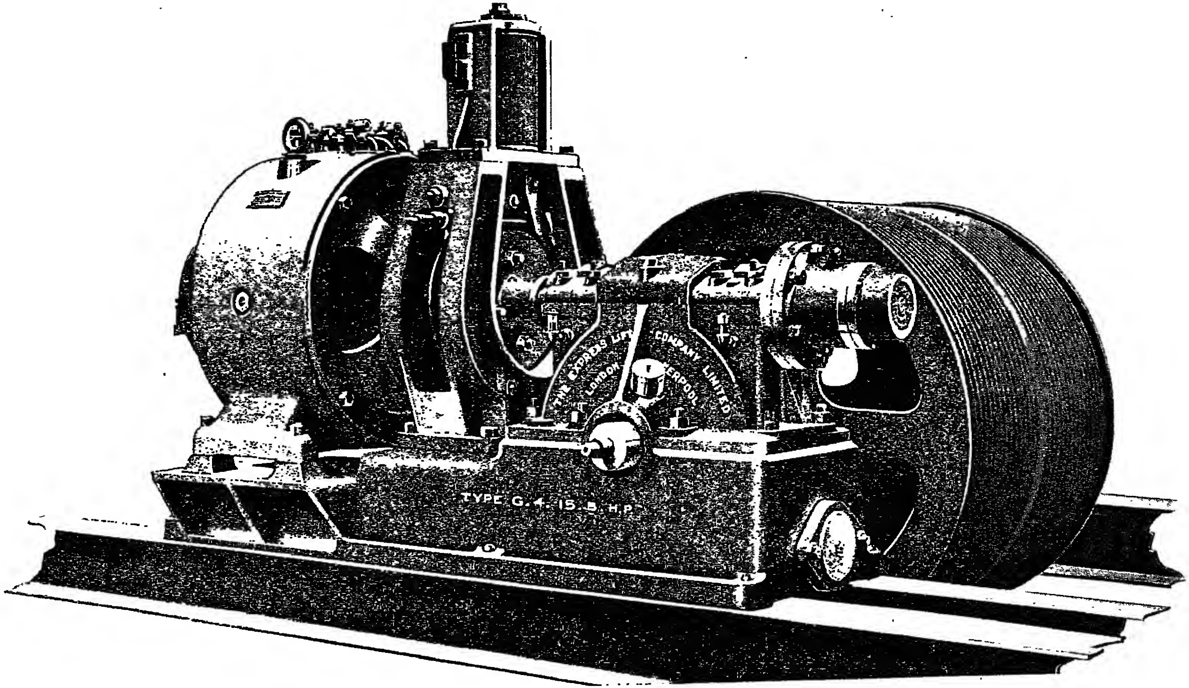
*Brown Boveri, Ltd.*

*Fig.* 153. A three-phase commutator motor driving a ring-spinning frame, with automatic speed regulation by brush-rocker adjustment.

two bell-crank levers, the rollers at the ends of which rest on two cams. One of these varies the speed with the reciprocating rise and fall of the ring-rails, while the other gradually speeds up the motor according to the increase in diameter of the cop, slowing it down again just before the operation is completed.

A ring-frame separately driven by a three-phase motor governed in the latter way is shown in Fig. 153.

The driving of mules forms an interesting exception to the statements




*Express Lift Co., Ltd.*

*Fig.* 155. Lift driving gear, drum pattern.

It is the rule to make the counterweight equal to the weight of the cage plus the average load, the latter being taken as 40 per cent. of the maximum. Each passenger is reckoned to weigh $1\frac{1}{2}$ hundredweights, and to occupy 2 sq. ft. of floor space. The above value of counterweight enables the most economical size of motor to be used. As a rough guide it will be mentioned that to move a load of 9 cwt., or 6 persons, at 100 ft. per min., a 4 H.P. motor is required; and at 200 ft. per min., 8 H.P. A speed of 350–400 ft. per min. may be taken as the maximum for buildings up to about 10 stories, but for higher buildings speeds up to about 700 ft. per min. are employed. Push-button lifts do not usually exceed 200 ft. per min., or 300 at the most.

In the design of the worm gear, it is frequently possible to make the mechanical efficiency somewhat less than 50 per cent., rendering it impossible for the cage to 'run back' or drive the mechanism by virtue of its weight. For ratios of 22 : 1 and 33 : 1, however, requiring a double-thread worm, the efficiency is necessarily higher, and it is the custom to compensate for this by the use of two independent solenoid brakes.

¶ Lift Motors.—The electrical equipment may be designed for either D.C. or A.C. working. As with crane operation, the former gives the more convenient control, on account of the greater facility of speed adjustment and braking. For direct current a compound motor is used; but the series turns, amounting to about 40 per cent. of the total excitation, are cut out as soon as acceleration is completed, the motor finishing the run as a shunt machine.

For alternating current, the slip-ring induction motor is the most satisfactory type, as it enables the starting torque to be varied in such a way as to start all loads smoothly. Recently, however, the use of the squirrel-cage motor has been increasing, employing a high-resistance rotor so designed as to give maximum torque at starting. Smooth acceleration for light loads is then afforded by the use of resistance steps in the stator circuit. For speeds of about 200 ft. per min. and over, two-speed motors are usually employed in order to obtain final slow-speed and regenerative braking, the speed change being effected by changing the number of poles, usually to three times the normal number. Starting is, however, always carried out ~~on the~~ high-speed winding; but the other is substituted when it is desired to slow down as a preparation for an accurate stop, the sudden negative slip causing the machine to function as an asynchronous generator and return power to the line. Since a two-speed slip-ring motor requires a double winding on the rotor as well as on the stator, the expense and complication are much increased by this modification, and the employment of the simpler squirrel-cage type is hence easily understood.

Repulsion-induction motors have been used for single-phase installations. The Ward-Leonard system is becoming general for high-speed lifts, and is of course applicable to all systems of supply, D.C. and A.C., of any frequency and number of phases.

¶ CONTROL GEAR.—At the time when the automatic control of lift motors was first standardized, the time-element starter with solenoid and dash-pot was the only self-acting control apparatus that was then fully developed; and it is not surprising that this pattern was employed for the purpose, and is still used in a large number of cases. Recently, however, industrial contactor practice has been followed by a number of designers, and both current-limit and C.E.M.F. acceleration are frequently met with. The cycle of acceleration and retardation is, however, practically the same for all types.

The diagram forming Fig. 156 gives a typical D.C. lift-control scheme, applicable to any type of apparatus. It will be seen to conform

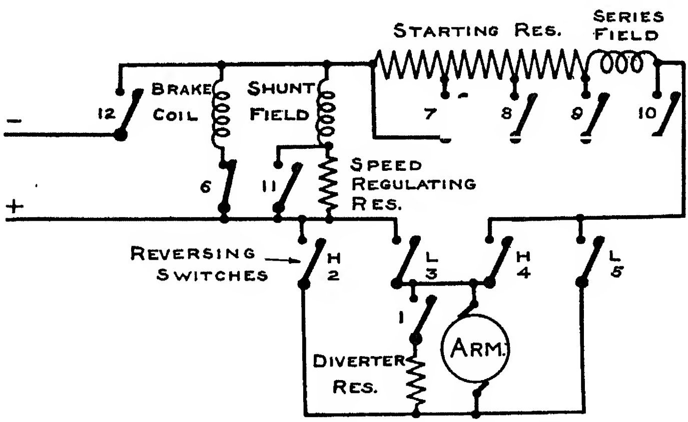



*Fig.* 156. Typical resistance control scheme for lift.

quite closely with the installations described in Chap. XIV, the components not usually figuring in a reversing contactor controller such as that shown in Fig. 128 being those specially required for lift-control purposes. The usual reversing line switches, numbered 2, 3, 4, and 5, will be recognized, these being alternately for hoisting (*H*) and lowering (*L*); and also the control resistance in its usual place in series with the armature, arranged to be cut out in three steps by switches 7, 8, and 9. But in addition there will be observed a fifth line switch, numbered 12, which completely disconnects the opposite pole from the line, and acts as a circuit breaker, opening the connexion if any of the safety relays, limit switches, gate switches, &c., opens or fails to close. Moreover, the series field will be seen to be provided with a switch numbered 10, which treats it as though it were an additional step of resistance, short-circuiting it after the others. Not only does this put up the speed and endow the motor with shunt characteristics, but the short-circuited field coils prevent a sudden change of flux in the magnetic circuit, causing the further increase in the speed due to field weakening to be smooth.

It is again usual, when the lift speed exceeds about 200 ft. per min., to employ a two-speed motor, consisting in this case of one designed for a 2 : 1 speed variation by the insertion of resistance in the field circuit. After normal full speed has been reached, therefore, switch 11 is opened by a further movement of the car switch, cutting in the regulating resistance, which quickly increases the speed to twice normal. A vibrating field-accelerating relay may be used to assist the latter acceleration.

As a preliminary to stopping, in order that the floor of the car may be brought accurately to the landing level, it is the practice with all but the slowest lifts to bring about a creeping speed. For this not only is the resistance cut out of the shunt field, but the series field and the control resistance are reinserted in the main circuit, and an additional or diverter resistance is connected in parallel with the armature by switch 1. Upon the power supply being cut off by opening the line switches 2 and 4, or 3 and 5, the diverter resistance forms itself into a dynamic brake. Finally, the friction brake is imposed by the opening of switch 6, completing the stop and preventing further movement.

Diagrams for lifts with other speeds are usually modifications of that shown in the figure. For goods lifts running at about 150 ft. per min. the field-regulating resistance would be omitted, and two steps of starting resistance might be used instead of three. For still slower speeds the diverter resistance would be omitted. For the faster speeds more than one step of field resistance, and further series and diverter resistance steps, would be used.

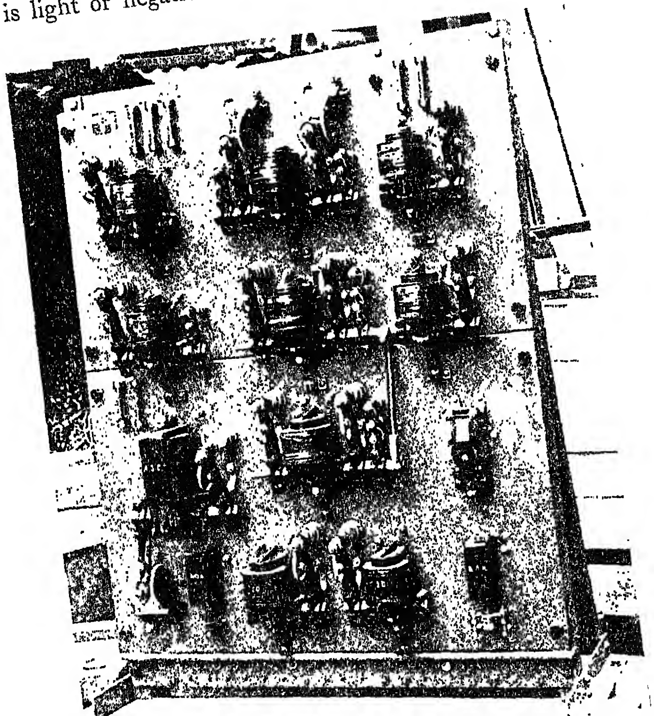
The scheme for A.C. motors can easily be compiled on the lines of the above, remembering that no dynamic brake and no speed adjustment by field regulation are possible. When double windings are provided with two-speed motors the change is effected by means of duplicate contactors.

The above full scheme could be carried out as it stands by means of shunt contactors and current-limit accelerating relays, exactly as in ordinary industrial control installations; and this is the practice adopted by several prominent manufacturers. Others use counter E.M.F. acceleration; while firms who specialize in lifts, and do not produce other forms of industrial control gear, employ a design of contactor that differs in several respects from the usual pattern.

Examples of both these features may be seen in the control installation forming Fig. 157. In this the double-pole units running down the middle of the board are the line contactors, the uppermost forming the 'circuit-breaking' member and the next two, mechanically interlocked with each other, being the reversing units. Flanking these on the upper panel are the four C.E.M.F. accelerating contactors, while the double-throw dynamic and solenoid brake contactor and the pair for dealing with the field-regulating resistance can easily be distinguished.

As regards the designs of the individual switches it will be seen that these are of the vertical solenoid and plunger pattern. The contacts also consist of large carbon buttons, gripped in split sockets of brass.

Other examples notwithstanding, there is still a great deal to be said for the original method of time-element acceleration. The loads in a lift cage are typically variable, and a motor with the correct resistance inserted to start it when fully loaded will accelerate too rapidly when the load is light or negative. On the other hand, if the first step is



*Express Lift Co., Ltd.*

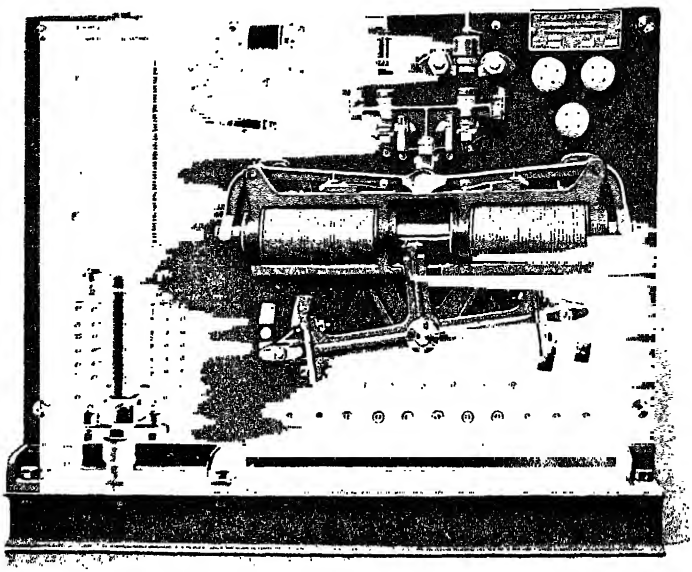
*Fig.* 157. Contactor control gear for D.C. lift motor. Note the solenoid form of the contactors and the carbon contacts. The double-throw contactor in the lower left-hand corner is for dynamic braking.

proportioned for smooth starting with a light load, the motor will not start on this step when the load is heavy; and with current-limit as well as C.E.M.F. acceleration there will actually be no start at all. Both D.C. and A.C. motors behave in this way, including the squirrel-cage machine with stator resistance; and a scheme is coming into use in which the first two or three steps of acceleration are governed by time-element relays, the remainder being by current limit.

The pure time-element scheme does not, however, require any addition to render it capable of accelerating any load smoothly, for the

process is carried out at the same rate for all loads. If the maximum weight is being lifted the motor does not start on the first one or two steps; but since it is an easy matter to employ a large number of contacts with a time-element distributing switch, there will be sufficient under all conditions to give gradual starting.

An example of this form of control gear, rated at a maximum of 12 H.P., is shown in Fig. 158. Like the great majority of such boards,



*Express Lift Co., Ltd.*

*Fig.* 158. Solenoid-operated control gear for lift.

it is composed of slate, with the resistors and connexions mounted at the back. The reversing switch is the most prominent feature, consisting of the horizontal double solenoid in the middle of the panel, moving the reversing contacts directly below. The left-hand solenoid would close contacts corresponding to switches 2 and 4 in Fig. 156, and the right-hand those corresponding to 3 and 5. It should be noted that current is never broken by this switch, ~~the heavy~~ contacts, opening vertically and situated immediately above the solenoid, actually making and breaking ~~the circuit. They are operated by~~ separate plungers at the outer ends of the solenoids, through the medium of bell-crank levers, and the length of the air-gap inside the coils is so adjusted that the strength of pull is not sufficient to move the upper contacts until the main plunger has completed its motion and reduced the gap. The

upper switch thus corresponds with 12 in Fig. 156, and has a magnetic blow-out at the right hand of the two breaks in series, to enable it to rupture the current effectively; but in the off position it also performs the functions of switch 1, as it connects the diverter resistance across the armature. There are small interlocking contacts just above each solenoid, for preventing both units from being energized at the same time.

The series and shunt accelerating rheostats, or the series only, if the shunt is absent as in the figure, are situated at the left of the panel, and are alike in design, the former cutting out resistance in the armature circuit and also the series field, as is done by switches 7, 8, 9, and 10 in the diagram; and the latter similarly increasing the current in the shunt field, performed by one switch only, viz. 11, in the previous scheme. These are sometimes interlocked to operate in succession, the field not being weakened until all the armature resistance is cut out; but it is sound practice to permit them to function simultaneously, when a simple mechanical interlock is fitted to prevent the shunt contact from travelling faster than the series. Both units are fitted with auxiliary contacts at each end of the travel, the lower ones to ensure that the main solenoid is not energized unless the rheostats are right down, and the upper ones to insert economy resistances in the various coil circuits when the processes are completed.

The general diagram has not been complicated by the addition of discharge resistances for the shunt-field winding and brake solenoid, but care is always exercised that neither of these is broken without there being a path for absorbing the persistent current, and also that the shunt discharge does not tend to energize and hold up the brake. With the former it is frequently possible to arrange the operation of the various line switches so that the armature is always left across the field at the moment of rupture.

The latter type of control gear, excellent though its record has been, is to-day being gradually supplanted by the contactor type, thus bringing lift control into line with general industrial practice.

¶ AUXILIARY SWITCHES AND SAFETY DEVICES.—One of the most important features of lift control is the provision of a sufficient number of auxiliary switches to ensure correct operation and safety under all circumstances. These are as follows:

(*a*) *Mounted on the Car.* (1) Car switch; (2) emergency switch; (3) slow-down switch.

(*b*) *Fixed to the Lift Well or Building.* (4) Door and gate contacts; (5) overtravel limit switches; (6) slack cable switch; (7) overspeed governor switch.

Of these the car switch is the master controller by which the operating coils causing the lift to move are energized; and the various safety switches, excluding the slow-down unit, are all connected in series with the lead from the line to the master switch, so that any untoward event will bring about the immediate stopping of the motor and the application of the friction and dynamic brakes.

The car switch is a compact model, designed to project as little as possible into the passenger space. It is of the reversing type, having an ' off ' position, to which the handle automatically returns when released, with from two to six ' hoist ' and ' lower ' points symmetrically disposed on either side of the off point. Three points would, for example, be required for the diagram shown in Fig. 156, and they would be employed in the following manner. To start in either direction, the switch would be moved to the second, or full-speed contact, which closes the appropriate line contactors ; the control resistance steps and the series field being then cut out in succession. Fast speed is obtained by moving on to the third contact ; and slow-down by

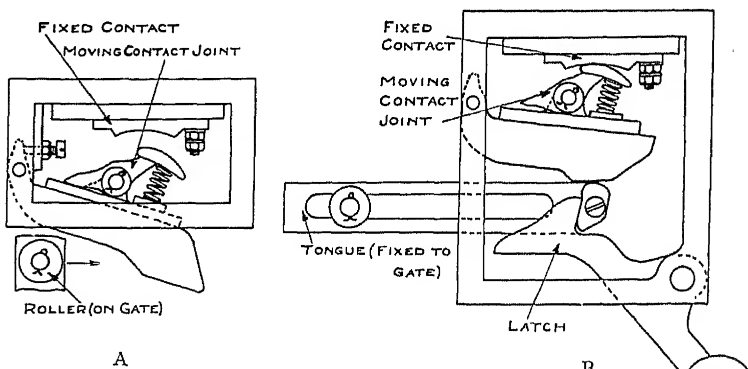



*Fig.* 159. Typical gate switch. A, switch only. B, switch combined with automatic gate-lock.

moving back to the first, when the diverting resistance is connected across the armature. Upon the handle returning to the ' off ' position, or any of the safety switches opening, all power is cut off from the motor, and the solenoid and dynamic brakes are left in operation.

In case anything should go wrong with the car switch a simple knife model, known as the ' emergency switch ', is often provided inside the car, which cuts off the supply from the former and brings about a stoppage, this provision being chiefly employed when a ' self-levelling ' device is added to the equipment. The same occurs if the car overruns its appointed travel at the top or bottom of the shaft, limit switches being stationed at these points which are opened by the car itself. There are usually two sets of these switches, which come into action in succession. The first merely opens the same circuit as the car switch, and does not prevent the return movement. But if it overtravels sufficiently a complete interruption of the mechanism is effected by a second switch, and a resumption must be brought about by some other person than the attendant.

If a gate leading into the lift shaft is not fully closed the motor is prevented from running by the failure to bring together the contacts

of a switch mounted upon the gatepost. The use of a similar interlock upon the car gate is at present regarded as optional; but it should certainly be compulsory, as the chances are that in its absence this gate

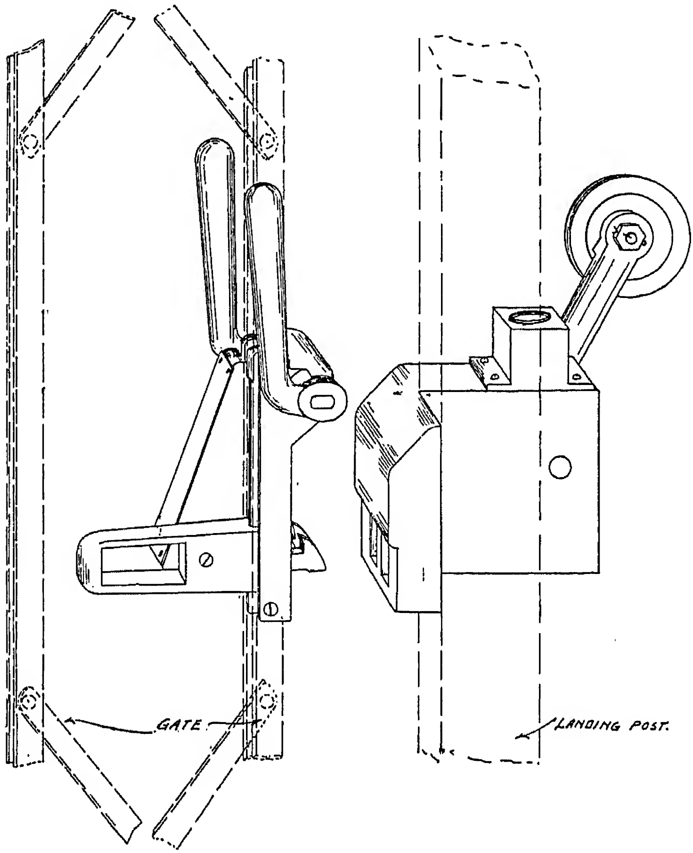



*Fig.* 160. Combined gate switch and lock, by the Express Lift Co., Ltd. The beaks enter the switch-box and close the switch. They are locked by a bolt coming under them and are unlocked by the action of a cam on the car which strikes the roller.

will not be closed at all. An important refinement consists of extending the functions of the switch at the landing to form a lock, preventing the gate from being opened unless the car is at a particular level. The illustration forming Fig. 159 A shows a typical gate switch with the cover removed to expose the contacts. A tongue projecting below the case directly supports the moving contact, and is pushed up by the small roller seen upon the edge of the gate. When locking is also to be carried out, the contact is moved by a horizontal strip or beak attached to

the gate, which is inserted into the side of the case, as shown in B. The tooth at the end of the strip then comes into engagement with a similar tooth on the left-hand end of a lever, the other end of which is external to the case and bears a rubber-tyred wheel. A cam is fixed to the car which moves the latter and unlatches the gate. The next illustration, Fig. 160, gives an external view of a slightly different design. A similar wheel and cam arrangement is usually adopted for the limit switches.

For lift mechanisms of the drum type a switch is also opened if the cable becomes slack due to an obstruction of the movement of car or counterweight, the striking gear of the switch being so placed that it is moved when the cable sags out of position.

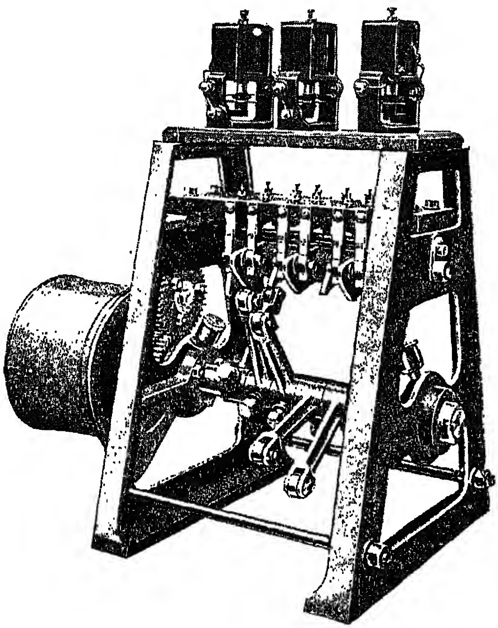
When the speed exceeds about 250 ft. per min. a simple limit switch is not sufficient to stop the cage at the top and bottom of the shaft, with the certainty that it will come to a standstill before harm is done. A master controller having contacts similar to those of the car switch, and wired in series with these, is therefore attached to the cage and operated by cams fixed to the side of the shaft. It can thus cut out the field resistance and bring about creeping speed, and finally apply the dynamic and solenoid brakes just as is done by the attendant. This method is preferable to the locating of a series of separate cam-operated switches in the shaft, as the latter scheme involves quite complicated wiring and laborious adjustment. A similar end is secured by means of a combined car and limit switch, according to another design.

There are two types of governor safety device applied to lifts, though the second is only used for high-speed models. The first consists of a centrifugal or inertia device which causes grips at the sides of the car to lock it to the guide rails as soon as an overspeed of 30 to 50 per cent. is experienced. The governor switch is worked by a similar mechanical device, but opens the control circuit at a somewhat smaller overspeed than is required to operate the grips.

¶ PUSH-BUTTON LIFTS.—Push-button operation is only resorted to when there is not traffic enough to justify the presence of an attendant, for the capacity is much lowered when there is no one in charge to ensure that the car is properly loaded and that time is not wasted. In addition, the higher lift-speeds are not yet practicable in the absence of an attendant. A further difficulty is that the whole operation is liable to be suspended owing to the non-closing of a gate by a user; and this kind of lift is hence most adapted for a club, hotel, or large residential establishment where it is handled by a fairly restricted number of people who are familiar with its operation.

The place of the car switch is taken by two different sets of push-buttons, namely, a button at each landing to bring the car to that floor, and a vertical row inside the car by which the destination is selected. There is more than one way in which the control gear can be designed; but the general method consists of providing a separate relay upon the

control board corresponding to each landing, connected to the appropriate call-button. The particular relay operated at any one time closes the line switches for the correct direction of travel and sets the motor running. A series of selecting switches are then operated by a rotary mechanism directly connected to the car (or to the drum shaft if the driving gear be of this type), and the circuit selected by the relay is thus opened when the car arrives at the proper floor, bringing about a stop. The process is repeated by the car push-buttons.



*Express Lift Co., Ltd.*

*Fig.* 161. View of floor-setting mechanism for push-button lift, with electro-magnetic relays for floor-selecting.

A typical selector switch mechanism, suitable for six landings, is shown in Fig. 161. The striker arms are clamped to the chain-driven spindle at the correct angles to operate two switches corresponding to each landing, one being opened and another closed immediately afterwards. This double switching is due to the necessity of providing for the movement of the car in either direction (exception for the top and bottom positions), depending on the relative position of the calling button.

¶ HIGH-SPEED LIFTS AND WARD-LEONARD CONTROL.—Although there is seldom justification for a greater car speed than about 350 ft. per min. in Great Britain, the much taller buildings in use in some other countries require speeds approximating to double this value. Those exceeding a figure of 450 may be classed as high-speed models, 600 ft. per min. being a common value that has become standardized for passenger work.

The gearless traction sheave is employed for this type of lift, consisting simply of a multi-groove pulley fixed to the shaft of the motor and functioning also as a brake drum. In some designs a cast-steel hollow shaft is employed integral with the armature spider.

It is customary to provide for five or six speed variations in each direction in the car switch, ranging from, say, 75 to the full 600 ft. per

min. This may be accomplished by rheostatic control, and there are equipments employing this method doing quite successful work. The speed control is, however, apt to be somewhat indefinite, the results differing rather widely according as the load is light or heavy, or as the car is going up or down. By the use of the Ward-Leonard system, however, the control is not only rendered simpler and more certain, but other important advantages are secured. The work of the attendant is rendered easier, and the acceleration and retardation are much smoother, the latter being due to the time-lag of the generator field-flux. Either an A.C. or D.C. supply can be used without interfering with the control. So successful is the variable voltage control that in spite of the use of three distinct electrical machines in place of one the system is notably economical in both consumption and maintenance, as compared with the resistance-control system.

As with most other Ward-Leonard schemes, the armatures of generator and lift motor are permanently connected electrically, the control being entirely effected upon the shunt field of the generator. The car switch forms the field rheostat, the resistance units being actually attached to the car itself, thus obviating a multiplicity of flexible connexions. What contactors are needed for reversal, &c., are small ones for dealing with the exciting current only.

One difficulty that has arisen in the past has been due to the falling-off in the regulation of the three machines with increasing load. Compounding of the generator field is not admissible for correcting this, as it leads to instability under some conditions of running. The centrifugal form of governor has been used, but is apt to cause hunting. Regulation by means of a series exciter is a more recent method that is employed by the General Electric Co. (U.S.A.), and has given successful results.

The exciter is mounted on the main shaft of the motor generator, and is connected to boost the generator shunt field. Since its own field is series wound and is connected in the load circuit of the generator, it will be seen that the voltage of the latter is augmented when the weight to be lifted is heavy, but weakened by the reversal of the exciter when the load 'overhauls' the motor.

An interesting example comprising twenty-four such equipments in the Equitable Insurance building of New York is described in the *General Electric Review*.[1] Each generator is rated at 25 kw., and the lift motor at 40 H.P. at a maximum speed of 1,200 revs. per min. There is a separate motor-generator unit for each lift, which may be started from a key-switch in the car as well as from the switchboard.

[1] See Callaway and Harrington, 'A Notable High-Speed Elevator Installation', vol. 29, p. 84, February 1926.

## XVIII

# ELECTRIC OPERATION OF STEELWORKS

THE driving of steelworks provides the most familiar example of a function for which electricity was for a long time unsuited. When electrification was first tried in these situations the experiment was an undoubted failure; and it is only within recent years, long after the electric motor has proved its supremacy in most other industries, that success has rewarded the persistent efforts of machine and control gear designers. Thus the methods whereby this achievement was made possible cannot but be of particular interest to those who are working for the continued progress of electric operation. Many of these methods are employed also in the working of copper, although the problems involved are of much less severity on account of the necessarily smaller scale upon which operations are conducted.

The special features of the metalworks that made electrification difficult are, first, the extremely heavy nature of the work to be accomplished; secondly, the great value of the product as compared with the factory buildings and equipment; and thirdly, the dependence of one process upon the others in the series. Of these the first imposed mechanical stresses and shocks upon the motor which it was initially unable to withstand; the second demanded rapidity of working, and especially of starting and stopping; and the third necessitated continuity of service on the part of every apparatus to avoid the holding up of the entire series. The average steelworks produces its own value in the shape of output every two months, and time is literally money under such conditions. The characteristics demanded are therefore robustness and power, to accomplish heavy work at high speed; and reliability, to enable this to be done without interruption.

For the first equipments ordinary industrial motors were tried, with manually operated drum controllers. Constant trouble was the outcome, however, and the more hardy traction type of machine was substituted. Better results were now given, but the performance was still far below the required standard. A special pattern was therefore brought into being, known as the 'Mill' motor, an example of which is shown in Fig. 162. It will be sufficient here to enumerate the chief advantages of the type, which rendered it equal to the demands of the situation.

First, the whole machine, and especially the frame, armature, and shaft, are made extremely robust. A frequent cause of stoppage had previously been the twisting off of the shaft at the driving end; and in addition to this being now constructed of large diameter, both ends were extended beyond the bearings and fitted with key-ways, enabling a disabled motor to resume duty after it had been turned round upon its bedplate. Secondly, the whole design was revised to permit of the

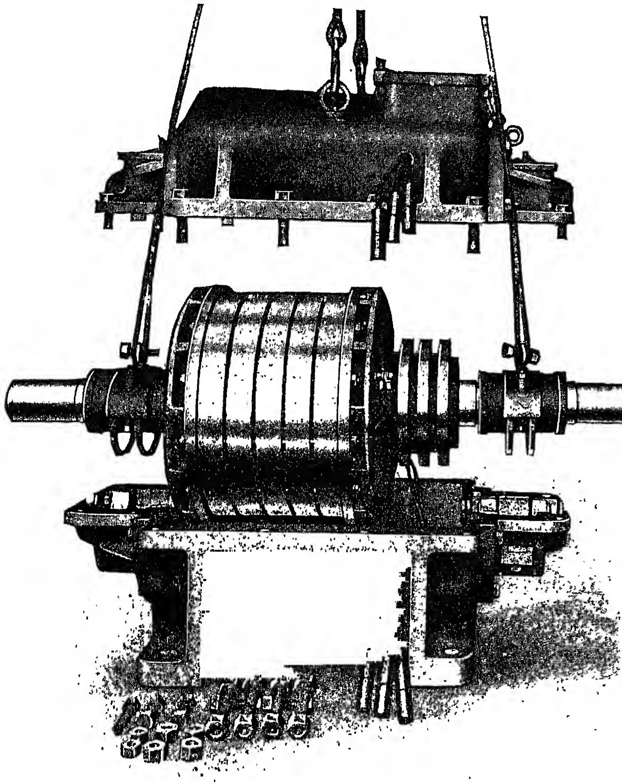
speedy replacement of any part. The illustration shows how the revolving element can be removed bodily by means of eyelets fitted to the bearing bushes. Thirdly, the electrical parts are effectively protected against dust and moisture and are designed to withstand the high temperatures experienced in the vicinity of furnaces.

Apart from the imperfections of the motor, however, trouble occurred through the shortcomings of the manual control gear. Not only was the drum controller wanting as regards robustness in view of the heavy currents and strenuous duty demanded of it; but its results, even in the hands of a skilled and experienced operator, fell short of the requirements as regards both economy of time and continuity of service. For every motor there is a safe maximum acceleration which cannot be exceeded without risk of break-down. The ideal control gear would enable this to be reached whenever desired, but never passed. With manual operation such results cannot be even approximately reached; for either the attendant will be unduly cautious, and therefore wasteful of time, or he will frequently overstep the mark, and at the least cause delay by bringing out the circuit breaker. These drawbacks are not shared by steam operation, but fortunately they can be entirely avoided by the automatic control of the motor.

The principles of automatic control gear have been already laid down in Chaps. X to XV, and it remains to give details of the plants employed in these special situations. It can be said broadly that contactor gear with current-limit acceleration is used for the smaller main drives and for the auxiliaries, while the large rolls are equipped with motor-generator apparatus. These methods, in conjunction with the new motors, have completely altered the position. Not only is the electric drive able to outdistance its older rival as regards output, economy, and reliability, but its use has radically improved the general conditions, lay-out, and practice in the whole works. The result has been that whereas at the outbreak of war there were about equal numbers of steam and electric mills in both Great Britain and America, at the present day electricity is sweeping the board by monopolizing all new undertakings and rapidly replacing steam in the older ones.

It will, therefore, be seen that electricity has the advantage in more respects than one. The deficiency having been made up, and indeed more than made up, as regards rapidity and reliability, the additional convenience and economy of electric drive have consolidated its position. Among the factors that have contributed to this victory are economy of space, through the compactness of the motor, economy in running cost, due to its superior efficiency, and economy in man-power, since a comparatively unskilled youth can take the place of one or more qualified men. Apart from the improved efficiency of the motive source while fully loaded, very important savings are effected in the transmission of power and during times of light load. To avoid a multiplicity of boiler-rooms, transmission of steam was customary to supply the various engines of the old plants, involving a loss in the vicinity of 40 per cent. as compared with approximately $\frac{1}{2}$ per cent. for electric work-

ing. Under no-load conditions, furthermore, the power consumed by a steam-engine is about 20 per cent. of the normal full-load demand, as compared with about 3 per cent. for the electric motor.



*General Electric Co., Ltd.*

*Fig.* 162. Mill motor.

But the greatly improved transport facilities introduced by the various forms of electric crane have probably exercised the greatest effect upon the design of the works themselves, as these have rendered it possible to move the heaviest and most awkward masses with ease, thus keeping the floor clear of obstructions. A centralized compressed-air supply was rendered unnecessary by the convenience of the small electric compressor. Other advantages of electrification, which need not be mentioned in detail, have also contributed towards its success. Sufficient has been said to indicate the conditions and requirements attending the

provision of the control gear, and particular attention will now be given to the individual plant.

The principal pieces of equipment that go to make up the modern metalworks are as follows :

(*a*) *Main drives.* Large main rolls, variously classed as blooming mills, cogging mills, plate mills, &c., requiring up to about 18,000 H.P. per set; smaller mills, requiring up to about 500 H.P., including small versions of the above besides wire, rod and strip mills, and others.

(*b*) *Mill auxiliaries.* Live rolls ; lifting or tilting gear for three-high mills ; screw-downs ; manipulators and side-guards.

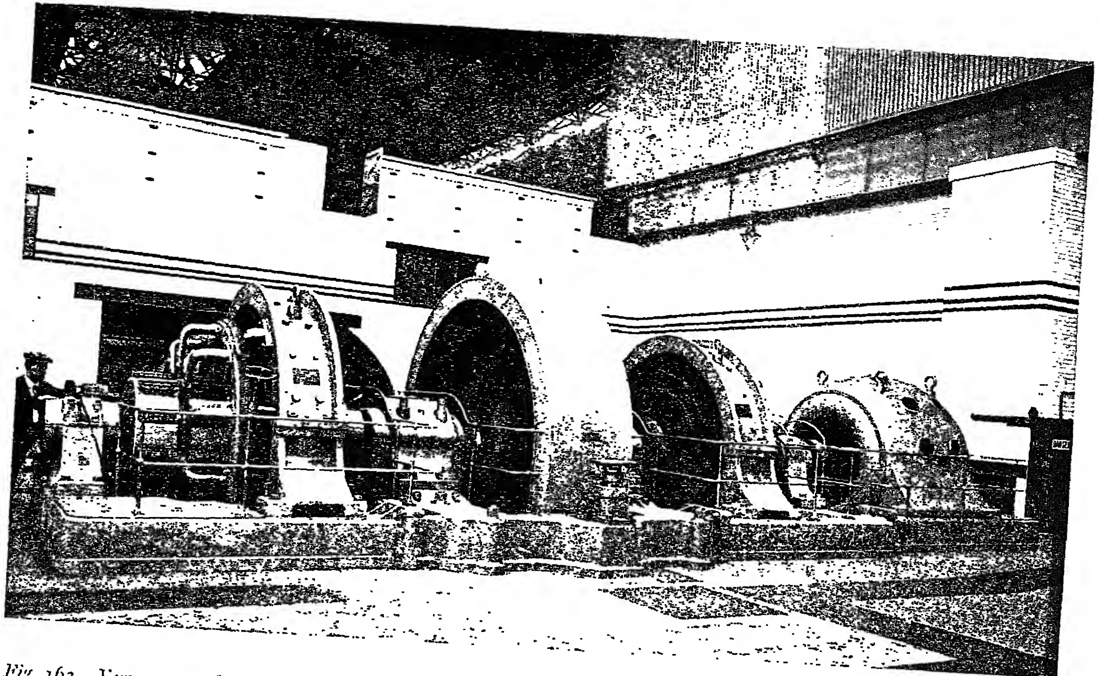
(*c*) *Transport equipment.* Overhead cranes ; jib cranes ; charging machines ; furnace hoists ; forge cranes ; ladle cranes ; soaking pit and stripper cranes.

(*d*) *Other equipment.* Hot saws ; air compressors ; Bessemer converters ; metal mixers ; plate rolls ; shearing machines ; lifting magnets.

¶ MAIN DRIVE OF ROLLING MILLS.—The main rolls consist, as most engineers area ware, of an arrangement for dealing with the metal while in a hot and plastic state, resembling closely the domestic mangle on an enormously magnified scale. But while many mills are like this familiar apparatus in being ‘ continuous ’, that is, in rotating constantly in the one direction, many others, especially among the larger examples, reverse their direction of running for every ‘ pass ’. There are two considerations which would permit continuous working: first, the use of a ‘ three-high ’ mill, together with a lifting or tilting floor or ‘ roll table ’ in the case of the large rolls, as indicated in Fig. 171; and secondly, the comparatively light weight of the product, enabling it to be passed by hand over the upper roller to enter the next pass at the same side as the previous one. These points in the mechanical design are closely associated with the electrical drive and its control.

Of these two alternatives, the reversing drive is the more common, but presents the greater difficulties, as far as the heavier mills are concerned. The driving requirements for continuous working do not involve the repeated quick stoppage and equally quick reversal of machinery possessing a considerable amount of inertia. But they do include the supply of power to the roll motor to enable it to cope with a widely and violently fluctuating load ; and they should preferably include the adjustment of the speed in such a way that the roughing stages are carried out more slowly than those at the conclusion of the process, when the metal is colder and of smaller cross section. With these requirements in view, and following along the lines of the discussion in Chap. XV, it is not difficult to arrive at the conclusion that, in order to avoid serious fluctuations in the demand for power, the services of a fly-wheel are demanded. This may be associated with the driving motor itself for a continuous drive, but for a reversing equipment an Ilgner motor-generator set incorporating the fly-wheel is necessary.

So great are the services of variable voltage control, however, in appro-



*English Electric Co., Ltd.*

*Fig.* 163. Ilgner set at Clydebridge operating a three-high non-reversing plate-rolling mill. Note the position of the fly-wheel between the two generators which are connected in series. The induction motor is rated at 2,500 H.P. at 500 R.P.M., but the set delivers a peak load of 13,000 H.P.

priately grading the speed of a continuous mill, that the Ilgner set is sometimes installed also for large units of this class, leaving the smaller ones to be operated by wound-rotor induction motors with fly-wheel and slip regulator ; an example of the former being the 13,000 H.P. (max.) equipment at Clydebridge, installed by the English Electric Co., the fly-wheel set of which is shown in Fig. 163. Since it is not an economical proposition to reduce the speed of an induction motor for the earlier passes, a compromise is effected by adopting a constant speed at all stages that is as high as circumstances will allow; but a certain reduction of output is inevitable, the saving of which is one of the advantages of the Ilgner system.

For continuous mills the fly-wheel balancer set, operated through a rotary converter as an intermediary, forms an alternative solution, such a set being described briefly in Chap. XV, p. 219.

Particulars relating to actual examples of steelworks drive will serve to illustrate the above principles, and for this purpose a rolling mill in South Wales equipped by the General Electric Co. will be first cited. To begin with, the capacities of the three principal machines are as follows :

Driving motor, 6,000–18,000 H.P., at 1,600 volts.

Generators, 4,500 kw. total (three in series).

Induction motor, 3,000 H.P., 2,750 volts, three-phase.

The driving motor is in reality a double one, consisting of two armatures on the one shaft and between the same pair of bearings, and possessing a duplex field. This arrangement, in preference to the use of a single large unit, keeps the inertia of the moving parts from becoming inconveniently large, and thus facilitates quick acceleration. The continuous capacity of the machine is 6,000 H.P., but it is designed to develop three times this amount for short periods without mechanical or electrical break-down and without brush-sparking. When rolling mills were first electrified a voltage of about 250 was adopted ; but for this set 1,600 volts is generated by three dynamos on the one shaft, each developing 533 volts, and all driven by the one 3,000 H.P. induction motor.

From the above figures it will be seen that the maximum load on the generators is six times the normal rating of the induction motor driving them ; and allowing for the small overload peaks reaching the mains, the highest load peaks are still five times the maximum load on the line. The great utility of this system in reducing power-supply charges is thus evident. As the demand on the generators of such equipments has been shown to vary during acceleration by the entire continuously rated horse-power per second, and at more than twice this rate during retardation, the equalizing effect of the fly-wheel is very necessary. Such violent fluctuations as these would be extremely troublesome to even the largest supply system, not to mention the comparatively small private generating equipments that many metalworks rely upon, deriving their power largely from furnace gas. A typical record of the fluctuations of both load and speed in a series of seven passes turning

out a comparatively light section is given in Fig. 164. Measurement of the areas will show that 24·25 per cent. of the input is returned to the fly-wheel by regenerative braking.

If the power consumption of the driving motor were examined, two sources of economy due to the Ilgner principle would be apparent, as compared with resistance control. During each acceleration period half the energy drawn from the line would be dissipated in the resistors of the latter scheme, a loss which is obviated with field regulation.

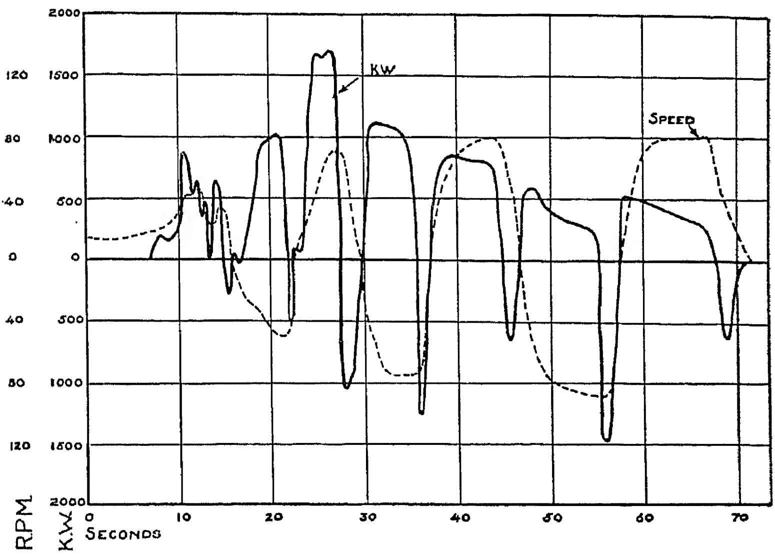



*Fig.* 164. Typical fluctuations of load in kw. and speed, showing a series of seven passes in turning out a section in a comparatively small mill.

Again during retardations the whole of the energy in the rotating parts of the driving motor and mill would be wasted in some form of dynamic brake, whereas the motor-generator system gives a considerable negative peak in the power line on each of these occasions, showing that the surplus energy has actually been restored to the fly-wheel, ready to be re-employed at the next acceleration.

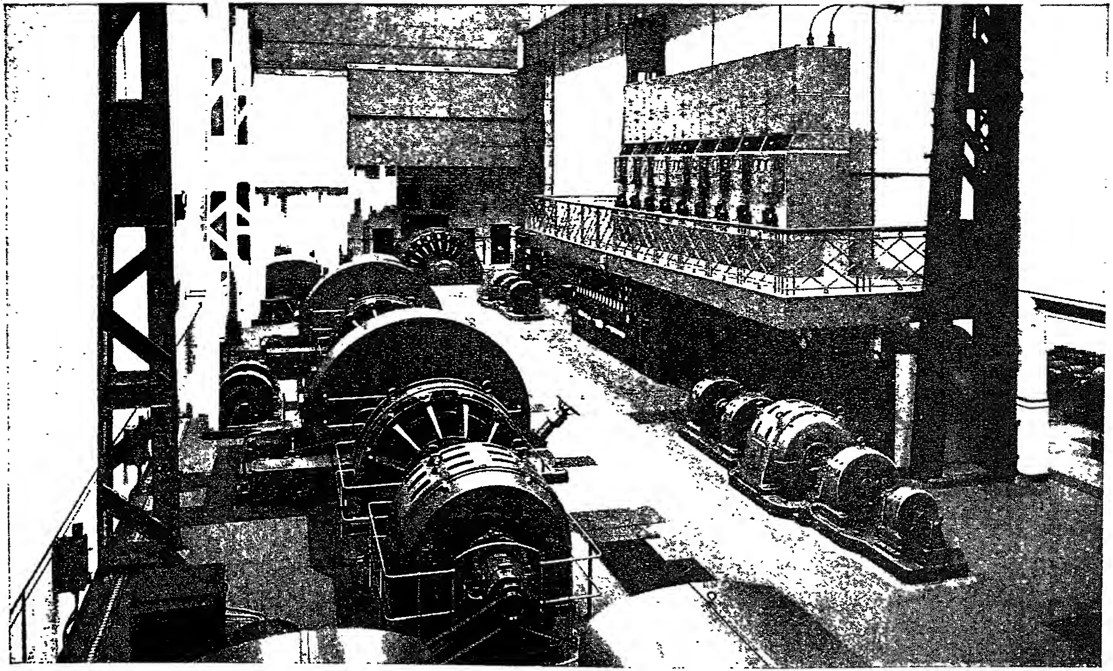
The excitation for all the machines is derived from a separate motor-generator set, here consisting of a synchronous motor and three exciters. Of the latter, one supplies the field of the D.C. generator; a second that of the driving motor; and the third excites the synchronous motor and the exciters themselves. Power-factor correction is effected by the over-excitation of the synchronous machine, while the control of the driving motor is carried out by the regulation of the generator exciter field. A certain amount of control for speeds above normal is effected upon the field of the driving motor exciter.

A liquid slip regulator is employed with this equipment, consisting of a rectangular sheet-steel tank containing three immersed pots of square section, but with narrow passages formed in two opposing sides to permit of an efficient circulation of the electrolyte through them. The moving electrodes are supported by flexible cables that pass over pulleys fitted with ball-bearings, and are then led to pulleys on the shaft of the torque motor. A view of this rheostat was given in Fig. 145.

Another interesting example of mill drive, by the English Electric Co., is seen in Fig. 165, where all the electrical components except the control platform are shown in the one picture, the missing feature being shown separately in Fig. 166. At the far end of the room is the double-armature motor, having a peak capacity of 14,000 H.P. at 50 revs. per min., driving a 42-in. reversing plate mill with 9½-ft. rolls, the actual mill being situated in the room beyond. At the other end of the machine room, but not included in the figure, is an exactly similar motor driving a 40-in. slabbing mill, and the duplicate control equipment can be seen for these two machines.

First, the incoming 3,000-volt power supply is dealt with by the cellular switch gear on the gallery to the right, a D.C. distribution board being situated below this. The two Ilgner fly-wheel sets are on the left, arranged with their shafts in line and normally connected by a flexible coupling; while the synchronous exciter sets for these are on the right and partly under the gallery. There are no less than four exciting generators in each, being from right to left a bucking exciter for the driving motor, a main exciter for the latter and for the exciters themselves, and, on the far side of the synchronous motor, exciters for the generator and for this motor. There are two dipper-type liquid slip regulators working in parallel for each set, these being all partly visible in the immediate foreground and at the far end of the room. A fuller view of one of these was given in Fig. 146. The only remaining item is the small motor generator on the extreme left, which is used to supply heavy current at low voltage for 'barring' either of the driving motors or the variable voltage generators. Half full-load torque at a few revolutions per minute can be obtained by plugging this set on to the main bars feeding the machine to be rotated.

A tube-mill drive is shown in Fig. 167, operated by a 400 H.P. induction motor, there being two distinct points of difference as compared with the above examples. First, the induction motor performs the driving itself, without the intervention of the D.C. machines; and secondly, it is not direct connected like the last driving motor, but is spur-geared. By the latter change the first cost is considerably reduced, as a much faster and smaller motor can now be used, and also the efficiency and power factor are higher. As an offset to these the maintenance costs are increased, owing to the presence of the gearing. Sometimes the fly-wheel is also located on the motor shaft, when its weight can be decreased in inverse proportion to the square of the speed; but the gearing must be made strong enough to stand the peak loads instead of merely the maximum that comes on the motor. The control gear is

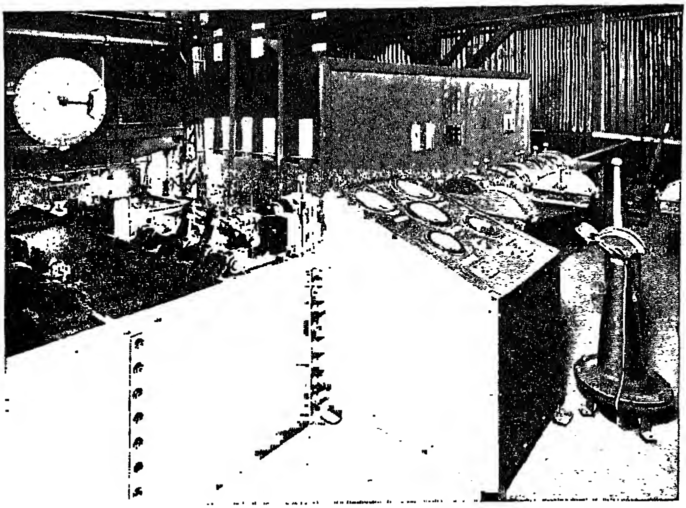


*English Electric Co., Ltd.*

*Fig*. 165. Machine room for large reversing motors at plate mills of the Consett Iron Co., Ltd. Two Ilgner sets are on the left, with liquid slip regulators at either end, a 14,000 H.P. plate-mill motor at the end of the room, and two exciter sets and the cellular switchboard for the incoming 3,000-volt supply on the right.

seen behind the motor, including a contactor type of slip regulator, with torque relay. The connexion diagram is exactly in accordance with that given in Chap. XIV, except that small auxiliary contactors are connected in cascade with those used for slip regulation.

¶ AUXILIARY DRIVES.—What has been said with regard to the great need for reliability in the case of the major pieces of equipment in a steel-works applies also to the smaller items, namely those driven by motors ranging from about 75 H.P. downwards ; for the failure of, for example,



*English Electric Co., Ltd.*

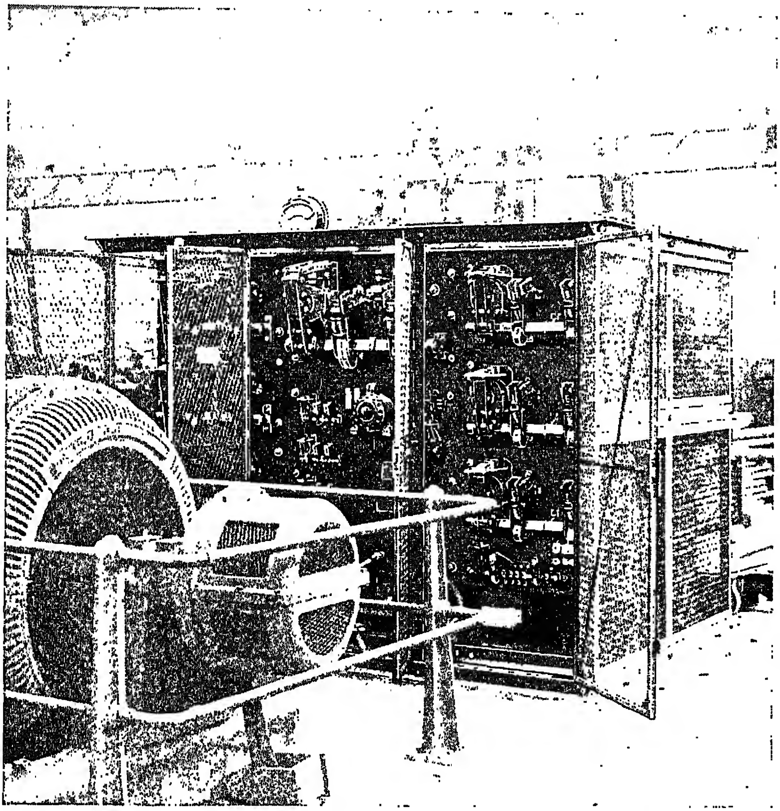
*Fig.* 166. Operator's platform overlooking mill at Consett Ironworks, showing metering desk, control lever for Ilgner set and main motor, and controllers for auxiliary motors beyond. Down on the left can be seen the main rolls, near live rolls, screw-down gear, and side-guards.

a screw-down or a live roll drive will hold up the mill just as thoroughly as the stoppage of the main rolls. At the same time the elaborate control apparatus provided for the very large motors could hardly be employed in the case of the smaller machines; and the principle is therefore observed of designing these with an unusual degree of robustness and compelling them to withstand the most drastic treatment that is meted out to almost any kind of electrical machinery.

On account of the strenuous nature of the conditions with which such plant has to comply, it is usual to have regard to this very service when designing contactor gear since no severer duty is likely to be encountered; while the 'mill' motor was specially evolved for such situations.

Four of these auxiliary motors are shown associated with a slabbing mill in Fig. 168, which well exemplifies their application. The two

largest, of 100 H.P. at 550 revs. per min., may be seen near the foot of the illustration, and operate the manipulators. One of the two 60 H.P. screw-down motors is near the top of the picture, and another of similar capacity, actuating the tilting gear, is near the left margin.

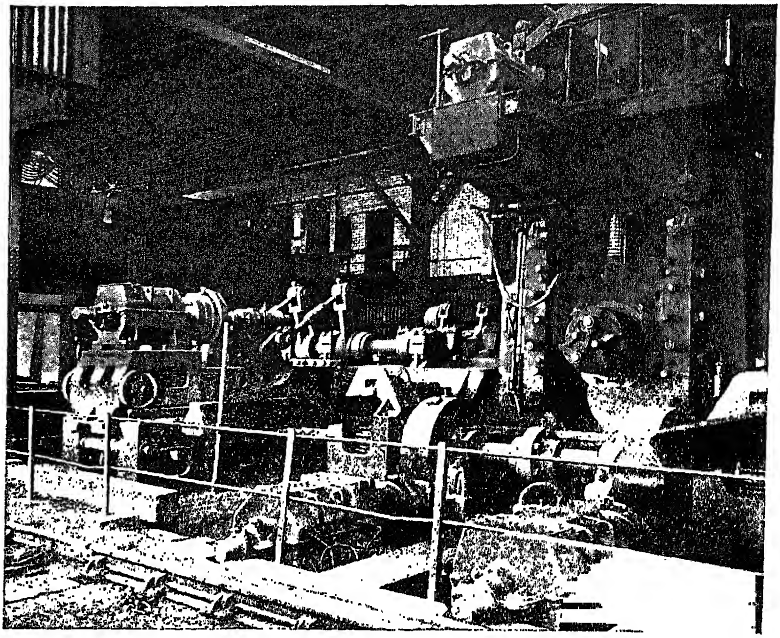


*General Electric Co., Ltd.*

*Fig.* 167. A.C. fly-wheel motor and contactor gear for tube rolling.

Many of the control schemes are of the simplest description, consisting of reversing contactor equipments designed for either D.C. or A.C. Thus the reversing line contactors, followed by three or four accelerating units, are the chief items. A fifth line contactor, giving double-pole switching, is however very often added to mill equipments. When the motion is simply backwards and forwards, without a pause at reversal, and when it is not required to stop accurately at some special point, then plugging is relied upon entirely for braking purposes. The operation of live rolls is of this description, the white-hot masses of

metal being lowered upon the comparatively small live rollers, which are motor driven through the medium of mitre-gearing, and thus advance the work to the mill. As the billet passes through the main rolls it is received upon the live-roll 'table' upon the other side, the rotation of which is reversed immediately the material has completed the pass. The contactor panel in Fig. 169 is an example of A.C. control apparatus for this purpose, the rotor circuit conforming with the diagram in Fig. 130;



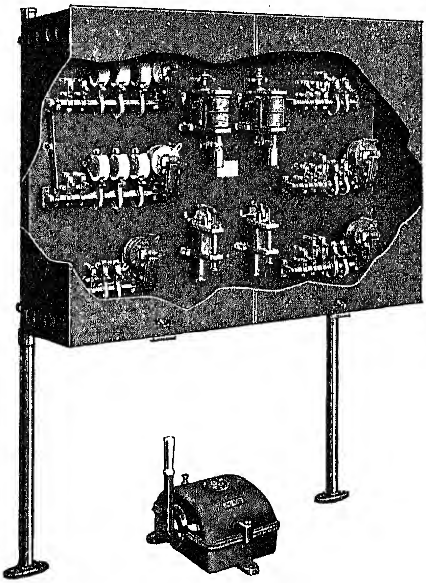
*English Electric Co., Ltd.*

*Fig.* 168. 100 H.P. and 60 H.P. mill motors driving slabbing-mill auxiliary gear at Consett plate-rolling mill.

the diagrams in Figs. 128 and 142 being appropriate for D.C. working. On account of the heavy starting torques required for this and most other mill auxiliaries, the usual motors employed are the series for D.C. and the wound rotor for A.C.; though the compound motor with powerful series turns has a certain vogue.

The general requirement of steelworks plant is that it shall operate at the maximum speed as much as possible, and consequently speed-control points are not usually needed upon the master controller. There are generally only two positions in each direction, namely, full speed and one with all resistance in, causing the motor to turn very slowly, chiefly for the purpose of taking up the backlash in the gearing before full torque is applied.

The separation of the main rolls is adjusted in large mills by means of motor-operated 'screw-downs', such as that visible in Fig. 168. For these a sudden stop is required as soon as the power is cut off, and a solenoid brake is often used in addition to the schemes just described, one being visible in the case just cited. If a compound motor is employed a dynamic brake may be substituted, while many mill authorities prefer to brake by simple plugging.



*British Thomson-Houston Co., Ltd.*

*Fig.* 169. Typical single-tier contactor equipment for auxiliary live rolls (cover broken away to show contactors).

Two other auxiliaries associated with the main rolls require a similar method of control to the screw-down. These are the side-guards, which are flat bars running parallel to the movement of the work, capable of being advanced towards the latter so as to push it from one groove in the rolls to the next; and the manipulators, which are steel fingers that project horizontally through openings in the guards and can be moved up and down. Their purpose is to turn the work over by inserting themselves under one corner of it and then rising. These two auxiliaries were formerly worked by hydraulic power, and sometimes continue to be operated in this manner after the rest of the mill has been electrified, though there is now no need for this differentiation.

Probably the best method of operating manipulator fingers is to drive them from a crank which makes a complete revolution at a time, and

is then stopped by a limit switch after the fingers have executed a single up and down cycle. The diagram forming Fig. 170 shows a simple non-reversing control scheme with dynamic braking. The latter is a most convenient type, but possesses the drawback that it requires the reversal of a series motor; and this is simply accomplished in the diagram. For forward running, contactors 5, 3, and 1 are closed, and the accelerating units 6 and 7 follow. For braking, 5 and 3 are opened and 2 and 4 are closed; which will be seen to do what is required. Duplicate limit switches may be employed, each alternately making and breaking circuit at successive operations, these being switched in alternately by means of a reversing controller as described on p 208.

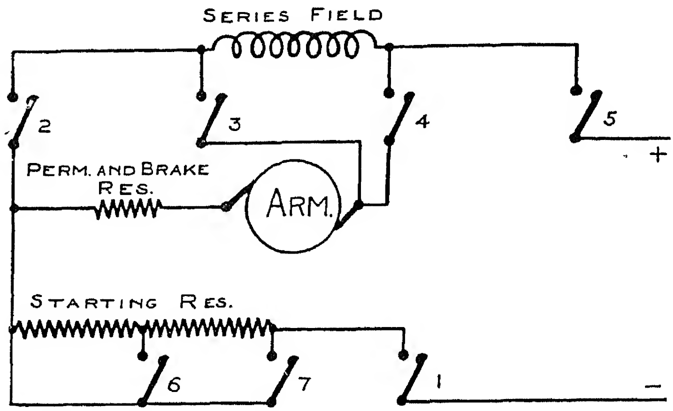



*Fig.* 170. Diagram of control scheme for manipulator fingers for non-reversing series motor and dynamic brake.

The braking resistor functions also as a permanent series resistance during normal running and its use in this position is worth noting. For motors with such a short running time as these auxiliaries, the acceleration has scarcely time to reach full speed, and it is frequently not worth while to cut all the resistance out, especially as the number of accelerating contactors is reduced by treating the last step as permanent. In addition, a more sudden stop is possible when resistance is left in the armature circuit, a fact that is of special use in connexion with side-guard control. In this case a slipping clutch is often interposed to prevent damage when the two guards come together or against the work.

Somewhat more elaboration is needed to control the motion of a lifting or tilting table, a device used with a three-high equipment to raise the work from the lower passage through the rolls to the upper, and vice versa. The mass lifted includes not only the work but the track upon which it runs, with live rolls complete, on both sides of the mill. As the combined weight may exceed 200,000 lb. and as it is required

to be moved into an exact position within three seconds, it will be seen that the mechanical as well as the electrical phase of the problem is of some magnitude. The diagram in Fig. 171 indicates the general method of carrying out the required function in the case of a lifting table, the tilting type being similar except that the outer ends are pivoted and only those near the main rolls are moved.

To begin with, the motor is driven in one direction only, and is stopped automatically when the crank keyed to its shaft reaches one or other dead centre. Thus the accuracy of the final positions is ensured, even if the angular movement of the crank be slightly too great or too small. The table is supported on bell-crank levers which are actuated from the

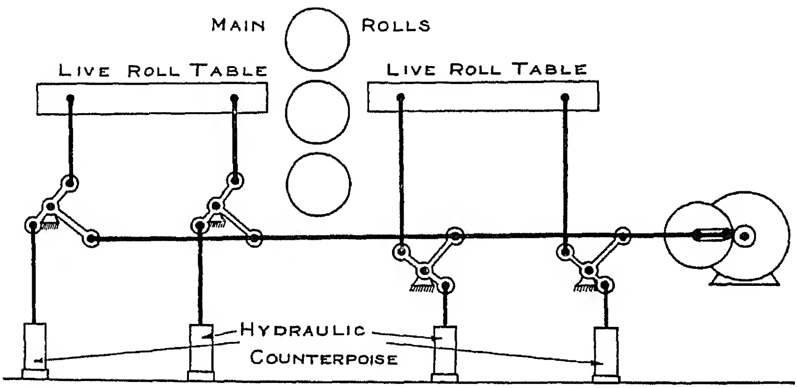



*Fig.* 171. Operation of lifting table of rolling mill.

motor crank by long connecting rods. Counter-balancing is now accomplished by hydraulic cylinders piped to a compressed-air chamber containing sufficient water to fill them, the pressure being so adjusted as to over-counterweight the table by about 25 per cent. when lowered and under-counterweight it to the same extent when raised. In this way both movements are assisted, while no addition is made to the inertia, as would be the case if solid counterweights were utilized.

The control gear should be fully automatic, the closing of one switch contact only being required to bring about the complete operation. In order to effect this a limit switch is opened just before the stop is to be made, which opens the contactors and applies the solenoid brake. With D.C. equipment a second limit switch may open shortly before the final one and lower the speed to a ' creeping ' value prior to the application of dynamic and solenoid brakes.

With the exception of the last example the auxiliaries so far dealt with have demanded simple automatic acceleration either without or with braking features. For a few other purposes speed control is needed in addition to either of the above schemes, and is provided by employing a master controller with contacts for every accelerating

contactor. Cranes and charging machines are examples of these requirements.

¶ LOCATION OF ROLLING MILL CONTROL GEAR.—The master controllers for any particular mill are located on pulpits or operating bridges commanding a complete view of the operations. The latter arrangement not only provides this to perfection but also affords a site for the control gear where it is well out of harm's way. When a bridge is not available the contactors must be housed in a separate room, on a raised platform, or in steel or expanded metal enclosures. A good example of such a mill control platform is given in Fig. 166. Not only can the driver see perfectly the working of the mill in the left of the picture, but the instrument desk is located immediately beneath his eye, enabling him to keep himself informed as to the current taken by the main motor, as well as its speed, and that of the Ilgner set. The lighting of a red lamp on this desk constitutes a warning that the speed of the fly-wheel has been reduced to its lower working limit. Control of the driving motor is effected by means of the pillar lever, and that of the various auxiliaries by the group of master controllers beyond the desk.

¶ STEELWORKS CRANES.—A number of the most interesting examples of electric crane are employed in handling the metal at its various stages of manufacture. While the methods of control broadly conform with those employed for cranes generally and dealt with in Chap. XX, it will be of advantage to describe briefly the special features of these types.

Molten metal is conveyed from place to place, and poured in a light or heavy stream, as desired, by means of a ladle crane. This is one of the overhead girder type, but possesses two trolleys which may be traversed from end to end of the bridge quite independently of each other. The larger runs upon the top of the girders, and handles the bucket-like ladle by means of duplicate chains hanging down outside the structure. The smaller trolley runs between the girders upon rails supported at their lower flanges. Its function is to raise or lower the bottom of the ladle in order to tilt it and pour the metal. There will thus be five motors, each controlled by a separate controller in the usual cabin, the two for hoisting being designed for low creeping speeds.

A forge crane is also of the girder type, but suspends cylindrical forgings under the steam hammer by an endless chain, the upper sprocket wheel being rotated by mitre gearing in order to turn the work at a maximum rate of about 5 revs. per min. Power is transmitted from an overhead motor of about 4 H.P. by means of a telescopic shaft with universal joints.

Soaking pit and stripper cranes handle the white-hot ingots by means of big vertical tongs, which must be supported rigidly to obviate the possibility of swinging, and which must be capable of rotation. An auxiliary mechanism also removes and replaces the pit cover, preferably from the same bridge position as for operating the tongs.

Charging cranes are among the most elaborate types in existence, and are for the purpose of inserting the materials into open-hearth and heating furnaces. To begin with, they possess the usual bridge and trolley motion; but suspended rigidly from the trolley is a vertical framework, supporting the charging bar at its lower end. Separate motors and control gear are provided to lift, slew, rock, and revolve this bar, to which may be attached a charging box or tongs. The control cabin is carried at the rear of the bar, and thus the control connexions for the lifting, slewing, traversing, and travelling motions, as well as for the main leads, must provide for a rotary motion. No less than fifteen collector rings are required for this purpose. Since all the motions are never required together, three or four controllers are usually made to do duty for all through the medium of change-over switches. A charging machine is a very similar piece of apparatus which travels along rails upon the floor instead of overhead.

¶ POWER DEMAND.—The sizes of motor in horse-power required for driving rolling mills are given in Table 24 in the Appendix.

# XIX

# FURNACE AND MINE HOISTS, AND UNDERGROUND CONTROL GEAR

THE electric hoist, whether it be a small one of about 100 H.P. for loading coke and ore into a blast furnace, or a large one of 1,000 H.P. or more for raising minerals out of a mine, is in reality a development of the electric lift; it is subject to the same kind of difficulties as the latter, and makes use of much the same kind of methods for overcoming them. The principal differences that obtain in the case of the hoist are: first, the power required is much greater; secondly, the load is in general more uniform; thirdly, it is the practice to employ balanced running, that is, two skips or cages are handled at a time, one descending as the other rises; and fourthly, in the case of mine hoists, the length of rope is very much greater, and the weight becomes a factor that considerably influences the design.

Broadly speaking, the methods in use for controlling hoists are as follows: (1) contactor controllers; (2) motor-generator systems; (3) liquid controllers. The second class includes both plain Ward-Leonard control and the Ilgner fly-wheel system; while the third may be modified by the addition of an equalizing converter.

Contactor control is available for the smaller equipments up to a maximum of about 1,000 H.P. As regards furnace hoists, not only is the power required comparatively small, but D.C. may be available; whereas for mine hoists the power supply is practically always in the form of A.C. With furnaces, again, the skip is only required to stop at the top and bottom of its travel, and automatic control is the rule; but the latter practice is an innovation of quite recent date in connexion with mine hoisting.

¶ ADVANTAGES OF ELECTRIC OPERATION.—Since both furnaces and coal mines are usually placed where coal is extremely cheap, it is of interest to note the advantages of electric operation that have given it the ascendency in what are undoubtedly unfavourable situations. These are principally as follows:

(1) The load is a very intermittent one for a steam-engine, and its efficiency is hence much reduced.

(2) Retardation must be carried out in connexion with a steam set entirely by means of frictional braking. With electrical drive, most of the braking is done on the motor, by returning power to the line. Not only is further economy thus secured, but much of the wear of the brake blocks is obviated.

(3) The turning effort of the electric motor is absolutely uniform, in contradistinction to the uneven torque of the engine; there is thus no tendency to 'flap' on the part of the ropes, and their life is prolonged.

(4) Electricity enables a saving in man-power to be effected.

(5) Safety devices, such as limit switches, overspeed devices, &c., are more readily applied to electrical control gear than to a steam engine.

As a concrete instance, the following figures were given by Rushmore[1] for the operation costs of each type for a 2,000 ft. hoist:

| | £ |
|---|---|
| Total cost of power per annum at 0·55*d*. per unit . . . . | 7,060 |
| Fixed charges on the excess cost of the electric over the steam hoist (approx. £5,000) . . . . . . . . . . . . | 500 |
| | 7,560 |

| | £ |
|---|---|
| 14,100 tons of coal at 14*s*. . . . . . . . . . . . | 9,870 |
| Boiler-house staff (3 men at 13*s*. per day) . . . . . . | 585 |
| One greaser . . . . . . . . . . . . | 180 |
| | 10,635 |

| | £ |
|---|---|
| Approximate annual saving with electric hoist . . . . . | 3,075 |

(representing interest on the investment of £5,000 at the rate of 61·5 per cent.)

The possibility of securing economy by electrical winding is of special importance to a colliery which has to obtain its coal from increasing depths, since the expense of the deeper hoisting may thus be directly neutralized and the life of an otherwise unprofitable mine prolonged.

¶ Furnace Hoists.—The problem to be solved in the design of a furnace hoist is to enable the skips to move alternately up and down upon the pressing of a push button or the simple closing of a switch, and to stop exactly at the right point whatever the load. As the latter may consist alternately of moderately light supplies of coke and heavy ones of ore, accurate registration can only be brought about by a slow-down to creeping speed well before the electrical and frictional brakes are applied. These must be entirely reliable to secure correct decking, and also for a further reason, namely, that an over-travel will cause a crash on the part of the skip and the hoisting gear. If a steel furnace is deprived of the services of its hoist for more than about twelve hours, and its molten charge is not run off, the latter will solidify, entailing an expense of something like £10,000 to repair the damage.

Two examples of furnace hoist will be described—for D.C. and A.C. respectively. For the former, the great advantages of diverter control, in securing both a very low speed and also dynamic braking, enable a straight contactor scheme to be employed. In a typical example there would be the usual four reversing line-contactors, a set of accelerating units with current-limit relays, and a normally closed contactor for applying the creeping speed and dynamic brake. The scheme of connexions is given in Fig. 172.

[1] See Rushmore and Pauly, 'Electric Mine Hoists', *Journal A.I.E.E.*, 1910, vol. 29, p. 289. Also see David, 'Electricity in Mines', *Journal I.E.E.*, 1925, vol. 63, p. 521.

The principal items of the scheme that call for comment are, first th diverter resistance and its control, and secondly the limit switche whereby the whole operation is governed. With regard to the forme the resistance is connected by a normally closed contactor when th shunt coil circuit is broken; but the contacts are held together by second coil connected in series with the current in order to produce a efficient contact. If the voltage were to fail, moreover, dynamic brakin would still be applied, as this contactor would automatically fall closed

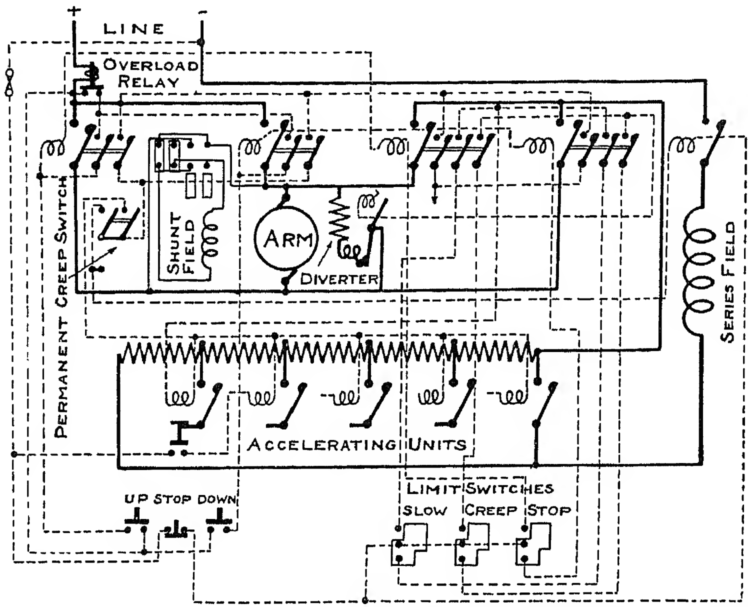



*Fig.* 172. Connexion diagram for D.C. furnace hoist control gear. Note that solenoid brake and connexions to most of accelerating contactors are omitted.

and would be pulled into closer engagement by current generated by the motor armature itself. Excitation is maintained by voltage from the armature, which is always connected to the shunt field in the righ direction by the field change-over switch situated between the first two reversing contactors and mechanically interlocked with them.

It is to the three limit switches that the scheme owes its automatic characteristics. These are marked respectively 'Slow', 'Creep', and 'Stop', and they are changed over by two sets of cams arranged on a large wheel that slowly rotates as the skips ascend and descend. Each switch has three positions, namely the middle one, in which all three contacts are joined together, and the outer positions brought about by the 'up' and 'down' cams respectively. In the diagram the installation is represented as being stationary in the 'up' position.

If it be supposed that the travel is nearing completion, the first limit switch to be opened inserts all the series resistance in the armature circuit, producing normal slow speed. The second switch connects the diverter resistance across the armature, giving the creeping speed ; while the third opens the line circuit, cutting off the power, applying the friction brake, and leaving the diverter resistance as a powerful dynamic brake.

When the skip is starting its movement, all but the 'stop' switch are short-circuited out of action by the auxiliary contacts on the right-hand pair of reversing units, causing the creeping-speed contactor to hold open (the series coil not being energized until just after its arma-

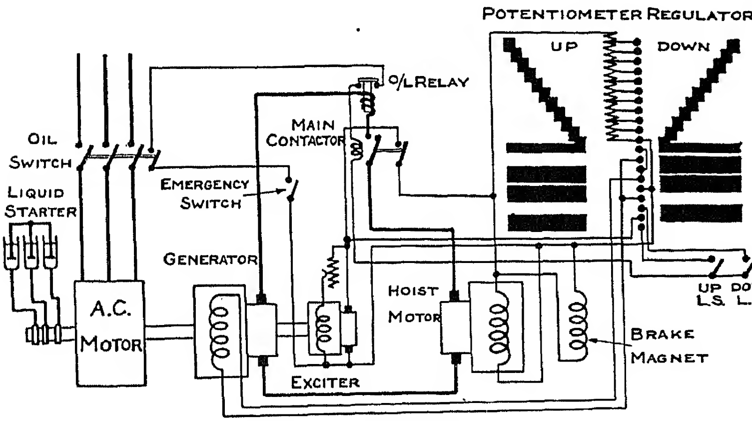



*Fig.* 173. Diagram of motor-generator control scheme for furnace hoist (Ward-Leonard principle).

ture has moved away from the lower pole-piece), and the 'slow-speed' contactor to close at once and begin automatic acceleration.

It will be observed that a fifth line-contactor is provided, giving double-pole switching. This feature, by breaking the circuit at an additional point, very much decreases any possibility of over-travel through the sticking of a line-contactor, since two would now have to fail simultaneously in order to cause trouble. Continuous creeping speed is obtained for rope inspection by means of the knife switch, which prevents the slow-speed and accelerating contactors from closing and the creeping unit from opening. An additional contact is added to ensure the circuits being dead when this change is made.

For the A.C. scheme, shown diagrammatically in Fig. 173, there is assumed to be no need to equalize the load for a motor of only 100 H.P., and a plain Ward-Leonard set without fly-wheel is therefore employed. Automatic control is brought about by means of a leading-screw moving a nut which follows the motion of the skip, rotating the potentiometer regulator through the medium of two cams, one for forward and the other for reverse running. The starting of the hoist is effected by the

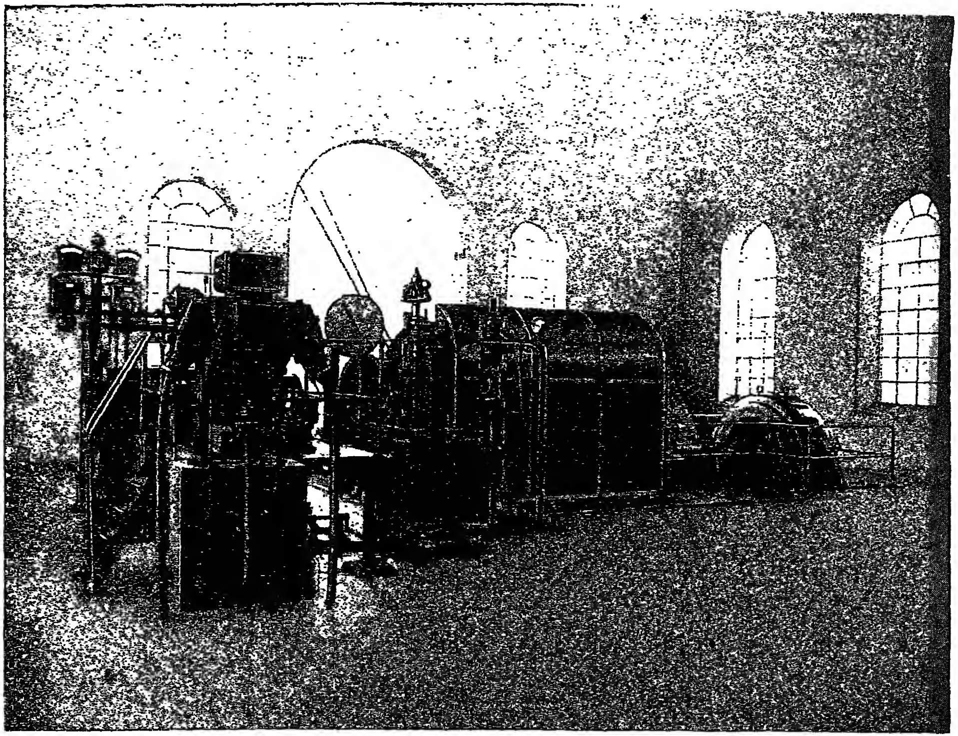
throwing over of a single lever, which places the regulator under tl control of the opposite cam to that which brought it to rest. Th action leaves the moving contacts in the creeping position, and tl motor gradually accelerates, runs, and retards again to creeping spee finally coming to rest at the exact end of the travel. The require changes of speed are governed by the curvature of the cams, the shapir of which is an important element in the design. A drum-type regulat is shown in the diagram, which also indicates other details of tl scheme.

¶ MINE HOISTS.—Although the principal difference between the windir gear for a mine and that for a furnace is in the greater size of the forme there are other distinctive features that may considerably increase i control problems. In the first place, although balanced operation is tl rule, one drum is always arranged to be declutched from the drivir shaft in order to adjust the length of the rope when it is desired to hoi from a different level. The empty cage has then to be lifted unbalance Secondly, although the maximum rope speed is usually from abo 1,000 to 3,500 ft. per min., it must be reduced to about 600 ft. per mi whenever it is desired to hoist men. Thirdly, the consequence of derangement of the gear may be so serious that the greatest possib care must be observed in connexion with the provision of safety devic such as brakes, over-speed and over-winding mechanisms, and the lik Fourthly, mine cages are often made with two, and sometimes thre decks, and each may require to be brought to the landing level, entailir a considerable amount of starting and stopping. The existence of mar levels also increases the amount of acceleration and retardation.

¶ SAFETY DEVICES FOR MINE HOISTS.—Whatever the type of windir and control gear selected, the requirements as to safety provisions a the same for all and are of great importance. For steam-driven hois a powerful brake was developed, consisting of two massive cheel applied directly to the periphery of the winding drum by means c compressed air, and this type is still standard for electrical workin The Whitmore brake is an example that may be seen on the hoist show in Fig. 174. In it the movement of the piston-rod releasing the chees weights and applying the brake follows exactly the movement of tl driver's lever. The weights alone are able to stop any load promptl independently of the motor (or engine) ; but if the driving power b applied, positive force is exerted by the air cylinder which enables tl brake to overcome the torque not only of the load but of the full motiv power as well.

When the friction brake is applied for any reason the weights a arranged to trip a circuit-breaker or operate the switch gear in such way as to cut off the power from the motor. The driver is provide with a lever whereby he can put on the brake instantly ; but means a also provided for causing it to function automatically under the follow ing circumstances :

(1) Failure of the supply voltage.



*General Electric Co., Ltd.*

*Fig.* 174. Electrical winding gear for large colliery hoist.

(2) Failure of air-supply to brake cylinder; a small auxiliary a
cylinder being provided which controls a trip-weight.

(3) Over-winding; there being limit switches on the pithead struc
ture, and also an over-wind protective device attached to th
depth indicator.

(4) Over-load; an over-current relay being connected in series wit
the hoist motor.

(5) Over-speed; protection being afforded by a centrifugal governo
or electrical over-speed device.

(6) Failure of excitation of driving motor (and generator in the case o
variable-voltage equipments); low-voltage or low-current relay
being applied to the exciter or included in the field circuit.

The above protection is provided for many electric hoists by mean
of an over-speed and over-winding protective device and depth indicato

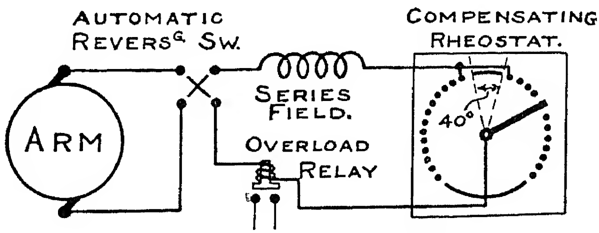
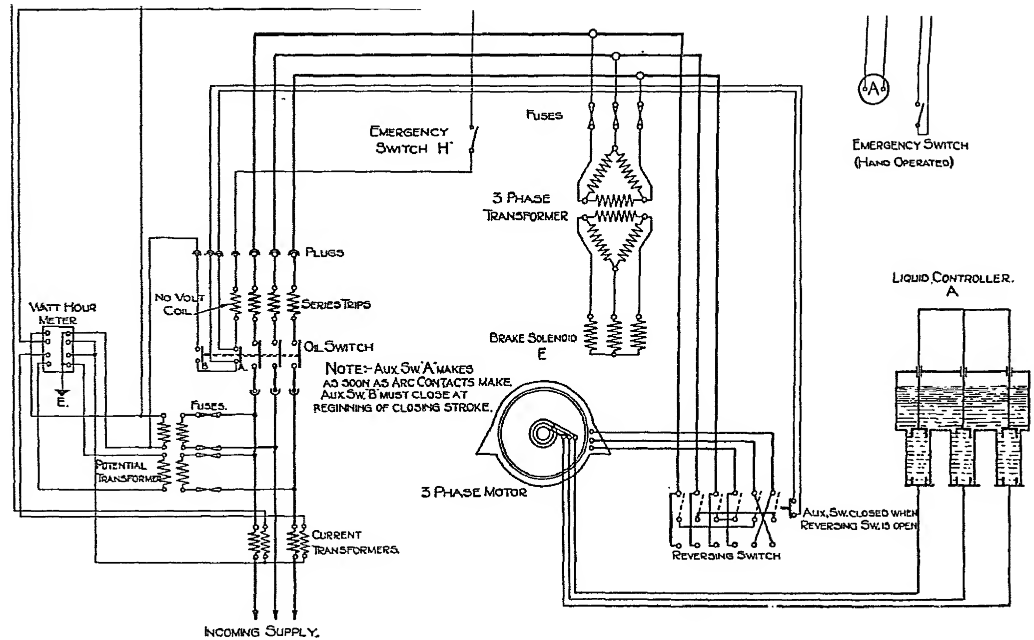



*Fig.* 175. Metropolitan-Vickers rheostatic device for prevention of over-speed, over-acceleration, and over-wind.

combined, derived from steam practice. Such an apparatus as designed for an A.C. winder is seen in Fig. 174. In this the centrifugal governor mechanism will be recognized at the top, and there are two vertical leading screws driven direct from the drum shaft. Nuts moving upon these screws represent exactly the position of each cage at any time, while there are also other nuts at predetermined positions for operating the safety devices if control is not applied by the driver at the proper points. The centrifugal governor comes into action after normal speed has been reached, and in the event of the speed not being reduced when retardation should begin, the brakes are applied without causing undue strain on the ropes.

Whatever the system, the intention is to take the control out of the hands of the driver should he at any time commit an error or give way altogether. He may, for example, start a wind in the wrong direction, or endeavour to finish winding at too great a speed; or he may become unconscious. The automatic apparatus will interfere in any of these cases, and bring the hoist safely and gradually to a standstill. The same result will follow failure of voltage or compressed-air supply.

A purely electrical over-speed device is shown diagrammatically in Fig. 175. A series generator is driven by the drum shaft, the armature of which is automatically reversed whenever the hoist motor reverses, by




*General Electric Co., Ltd.*

*Fig.* 176. Connexions for three-phase winder, showing triple-pot rheostat and reversing switch.

means of a mechanically operated switch. The current at each stage is, however, regulated by means of a series rheostat, the arm of which is slowly rotated by the depth indicator shaft. Thus resistance is inserted to keep the current constant, on the supposition that the speeds are correct at every point. If the hoist should travel too fast at any stage, a higher current than normal will be generated, which will pull up the relay contact and trip the main circuit breaker.

¶ Types of Hoist.—Since contactor gear is only employed for the smaller models, and is sufficiently exemplified in the Furnace Hoist Section, attention will be concentrated upon A.C. equipment controlled by a liquid rheostat and a D.C. hoist with Ward-Leonard control. Which of these two will be most economical in any particular case can usually be ascertained only by working out the initial and annual cost of each and capitalizing the latter. An excellent example of this procedure, due to Sydney Burns, is given in the *Mining Electrical Engineer*,[1] where no less than five different varieties of equipment for fulfilling specified conditions are tentatively designed and costed.

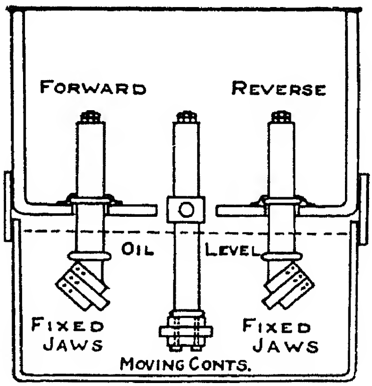
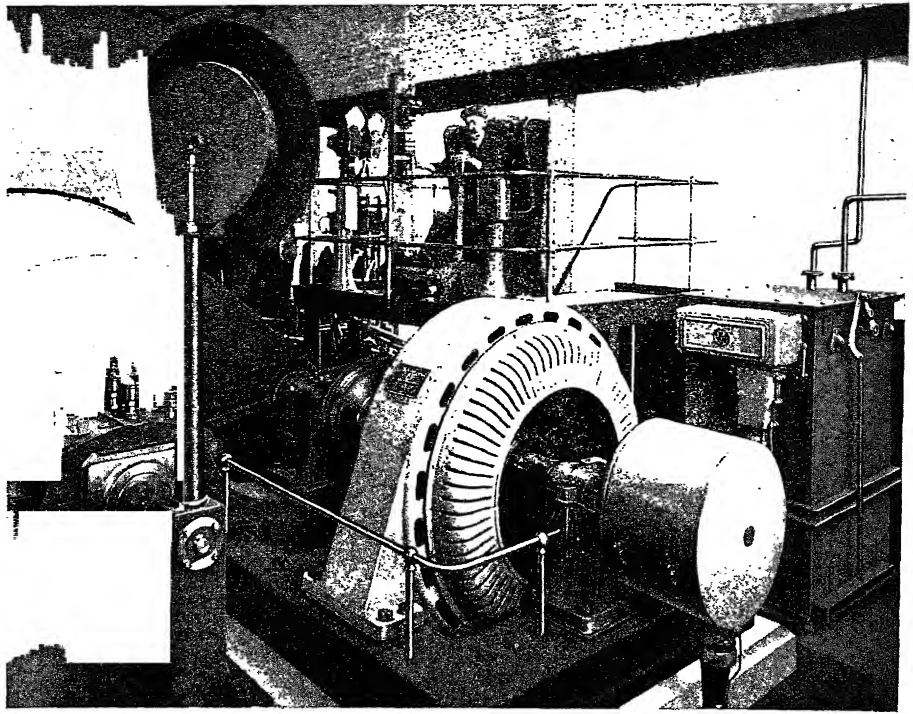


*Fig.* 177. Double-throw reversing oil switch.

An important factor in deciding upon the type of control is the means to be adopted for compensating for the weight of the rope acting against the hoisting motor when the wind begins. If a tail rope is permitted, the rope is always balanced, and a comparatively cheap sheet-metal cylindrical drum can be employed. Unfortunately, this practice is far from being general, and the more expensive cast-iron conical or cylindro-conical drums are therefore used to reduce the load peaks. Instead of modifying the drum, however, the Williams-Janney, or some similar variable-speed gear can be interposed between the motor and drums. This particular gear is a comparatively new oil-pressure device with an efficiency of about 80 per cent. which has recently been employed for such equipments, and is described on p. 324.

There are two main defects of the rheostatic method of control. The first is that half the energy drawn from the line during acceleration is wasted in the resistance, while all the kinetic energy at the conclusion of each wind is lost in brake friction. With Ward-Leonard control both these are saved; but there is a loss due to the inefficiencies of three instead of only one electrical machine, and there is additional expense in the form of higher fixed charges on the more costly plant.

[1] 'The Choice of a Small Electrical Winder', Feb. 1921, p. 143.



*British Thomson-Houston Co., Ltd.*

*Fig.* 178. Electric winder installation, showing liquid controller on right for 500 H.P. induction motor.

When, therefore, the power required for acceleration is great as compared with that needed for the steady-speed part of the wind, the Ward-Leonard scheme shows to advantage. An approximate indication is given by Stjernberg's formula,[1] which states as the condition for the economical employment of this apparatus that

$$\frac{MS}{QT^2} > 0{\cdot}3\,;$$

where $M$ = equivalent mass of moving parts at rope speed in lb.,
$Q$ = useful load plus friction in lb.,
$S$ = winding depth in feet,
$T$ = running time per wind in seconds.

It was shown mathematically in 1911 that Ward-Leonard control was preferable when the co-efficient exceeded 0·22, and was necessary when it exceeded 0·3; but recent improvements in the A.C. equipment, including the gearing, have increased the former figure to 0·3, and the latter to about 0·4.

The second defect of resistance control is that the sudden peak loads are imposed upon the line, and are in many cases more than the latter can supply; whereas the motor-generator system, when assisted by a fly-wheel, is able to absorb the peaks and equalize the load. An important criterion is thus the plant capacity feeding into the supply mains. The situation in this respect has of late undergone a marked improvement, through co-operation and interlinking between the pits in a given locality.

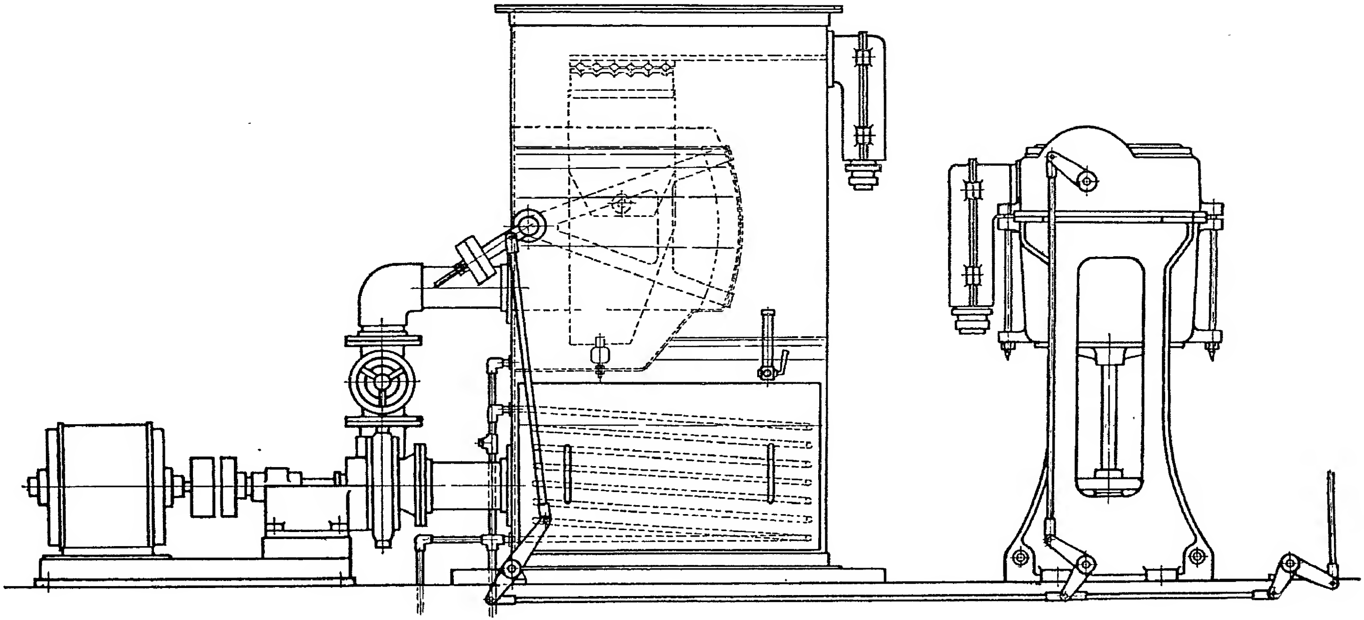
Finally, the cost of current directly affects the decision as to the type of winder, as it will decide whether it will pay to employ a cheaper but less efficient plant in preference to one that is more expensive in first cost but consumes less power.

¶ A.C. Resistance-controlled Winder.—The standard method of controlling an A.C. winder is by means of a liquid rheostat operated by a single lever in conjunction with an oil-immersed reversing switch or reversing contactors. For small hoists the triple-pot type of rheostat is employed, and this is illustrated in the diagram of connexions forming Fig. 176, showing the rheostat and reversing switch, which are operated by a single lever. The latter is in this case of the oil-immersed drum type; but a six-pole pendulum throw-over switch, as illustrated in Fig. 177, is also employed in this manner.

Reversing contactors are used in the winding installation shown in Fig. 178, which is especially interesting in that all the components of the equipment are clearly illustrated, including the liquid controller.

For the larger motors the weir type of rising-liquid controller is employed, an example of which is given in Fig. 179, showing the method whereby the one operating rod is able to manipulate first the reversing switch in either direction and then the weir of the rheostat. The restriction of the acceleration by the rate of rise of the electrolyte is a valuable feature of these larger equipments.

[1] See Stjernberg, 'Electric Winding', *Journal I.E.E.*, 1911, vol. 46, p. 192.

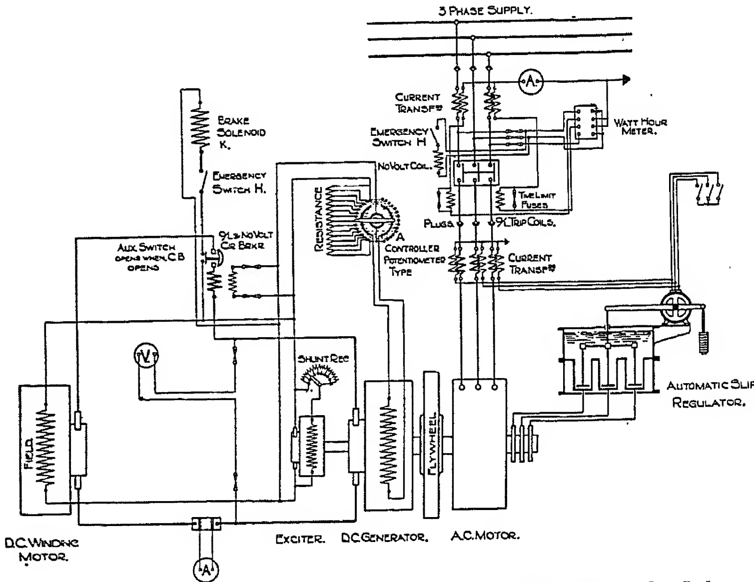


General Electric Co., Ltd.

*Fig.* 179. Sluice gate type controller with oil-immersed stator reversing switch, and motor-operated centrifugal pump for electrolyte on the left. The electrodes are shown dotted and supported in the upper tank on porcelain insulators.

The diagram is a comprehensive one, showing, in addition to the position of the main components, the location of the meters, instrument transformers, brake-solenoid and its transformer, main oil switch, and emergency switches.

¶ WARD-LEONARD WINDER.—A similar diagram for a motor-generator type of winding-control equipment, with liquid slip regulator, is given in Fig. 180, corresponding to the arrangement scheme in Fig. 181.



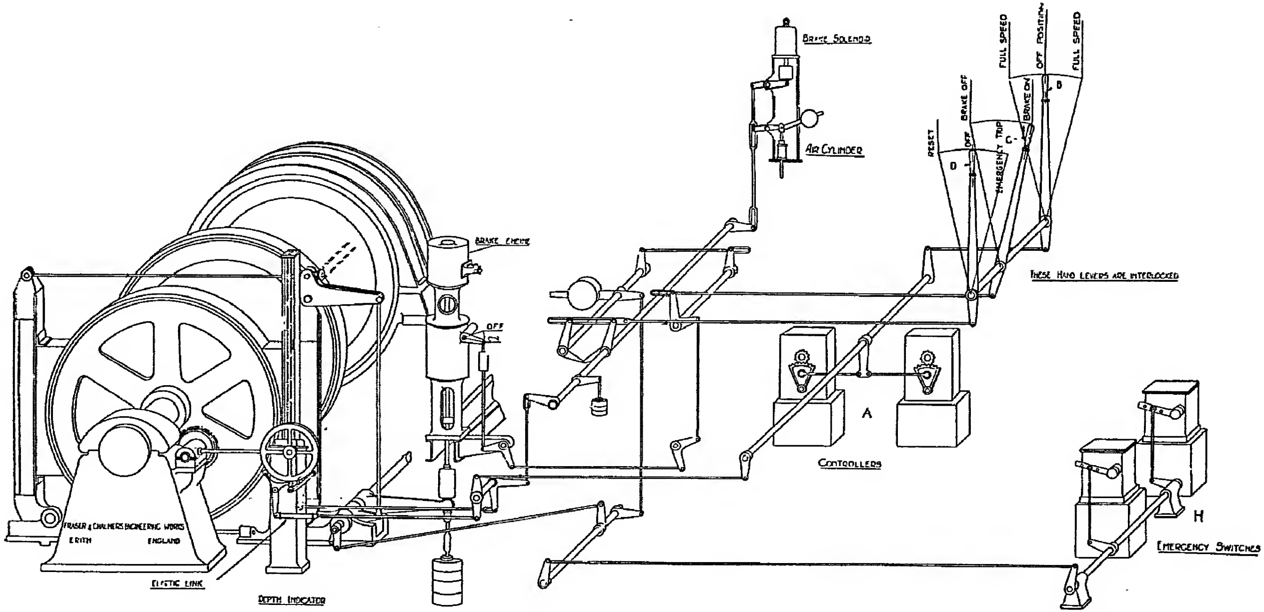

*General Electric Co., Ltd.*

*Fig.* 180. Connexions for Ilgner control of winder, corresponding with arrangement shown in Fig. 181.

As before, details as to measuring instruments and transformers, circuit breakers, and other minor components are given. The location of the current transformers for supplying the torque motor will be observed in Fig. 180, and also the energizing of the brake solenoïd from the exciter that forms part of the motor-generator set. An automatic regulator would be needed to keep the exciter voltage constant, but this is not included in the diagram. For other particulars of the Ilgner and Ward-Leonard schemes the reader is referred to Chap. XV.

The scheme arrangement diagram will afford instructive information as to the method of carrying out the control and protective principles that have already been given. A start should be made with the driver's levers, *B*, *C*, and *D*, which are the control, brake, and emergency levers respectively, and the steps in the control scheme traced out.

An interesting example of pure Ward-Leonard control (without




*Fraser and Chalmers, Ltd.*

*Fig.* 181. Diagram showing mechanical arrangements for operating winder with Ilgner system.

fly-wheel) is illustrated in Fig. 182, in which one of a pair of simil
hoists is shown and motor-generator sets for both. The particulars f
each installation are as follows :

Winding Motor—1,400 H.P. at 600 volts D.C. and 51 revs. per mi
A hand shunt-regulator is provided whereby the motor spe
may be varied from 45 to 65 revs. per min. for dealing wi
heavy or light loads respectively.

Generators—two with a total capacity of 1,200 kw., normally workin
in series at a voltage of 300 volts each.

Synchronous Motor—with a normal input of 1,400 kw. at 0·8 *leadi*
power factor, 3,200 volts and 750 revs. per min.

Two Exciters—one for the winding motor, generators, and bra
magnet, and one for the synchronous motor.

The latter five machines are mounted on the one bedplate, the sha being supported by four pedestal bearings, which it is particular interesting to note are of the roller type. The capacities of the thr principal machines should be compared with those of the Ilgner s given on p. 250, the induction motor of which is only about one-fif the size that would have been required if the fly-wheel had been absen

The starting of the synchronous motor is effected by an aut transformer scheme similar to that shown on p. 89. One double-thro oil-immersed switch is, however, used in this case. A period of on 25 seconds is required for running up and synchronizing. A plu board is provided whereby either or both of the generators on either s can be connected to either of the winding motors.

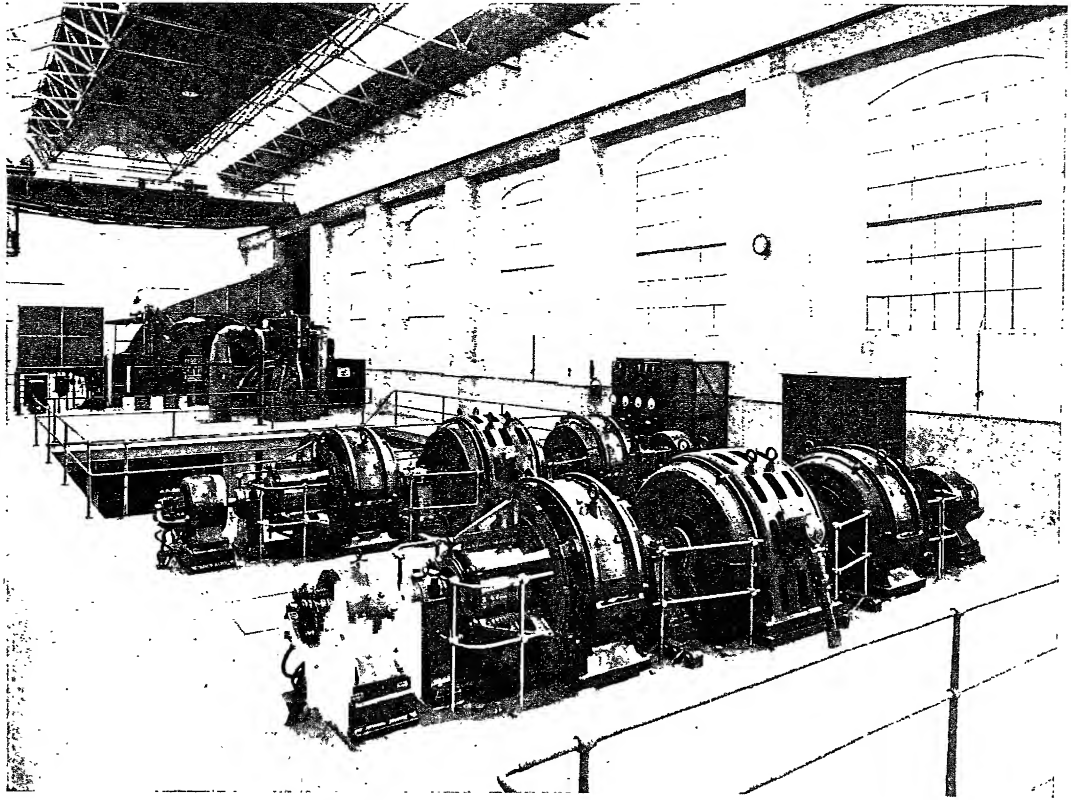
It is easily possible with this control to move the cage accurate an inch at a time, or to accelerate rapidly and smoothly up to full spee and bring about a quick stop by electrical braking alone, all by simp movements of the one control lever.

¶ Mine Haulage.—Coal trucks or 'tubs' are moved about the workin by means of rope haulage, the usual methods being those known the endless rope and the main-and-tail systems. With the former th rope is kept in continual movement at a speed of about 2¼ miles pe hour, and the tubs are clipped on to it as desired. By attaching th main rope to the front of a rake of tubs, and a tail rope to the bac end, and starting and stopping as required, a speed of from 6 to 10 mile per hour can be attained.

As with mine hoists, electrical power is generally supplied in th form of A.C., for which there is now the added reason that the ignitio of fire-damp is less liable to occur with this practice than with D.C Slip-ring induction motors are the rule for driving haulages. The mo usual capacities are from 50 to 250 H.P., at voltages ranging from abo 250 to 3,000.[1]

Although the winding gear rather closely resembles that for hoistin the problem is much simpler on account of the lower rope-speed an

[1] For power required by haulage schemes see Appendix, Tables 13 and 14.



*English Electric Co., Ltd.*

*Fig.* 182. Two motor-generator Ward-Leonard sets and one of two mine hoists at Llantrisant Colliery.

the absence of danger from falling. The most usual types of control gear are drum controllers for the smaller installations and liquid rheostats for the larger. Oil-immersed horizontal drum apparatus, as shown in Fig. 24, are particularly useful for the moderate-sized plants. Reversing installations are sometimes fitted with mechanical reverse gear ; but when a liquid controller equipment is required to start in both directions, a reversing oil switch must be interlocked with the rheostat, somewhat as shown in Fig. 179. Contactor equipment is finding increasing favour for this purpose, a good example having been shown in Fig. 129. The schemes are simple, closely resembling the standard diagram in Fig. 128. Frictional braking is the rule.

¶ FLAME-PROOF APPARATUS.—Electrical apparatus for use below ground must be free from all danger of igniting gas or coal-dust, and must therefore fulfil two conditions. First, the enclosures must be mechanically strong enough to resist the force of any explosion that can take place inside them ; and secondly, no ignition of the external atmosphere must take place as a result of the explosion within.

In the past attempts were made to exclude the gas by adopting a gas-tight construction, but it was found impossible to prevent the infiltration of fire-damp as a result of a sufficiently prolonged soaking. Present-day flame-proof models are therefore either made sufficiently robust to withstand a bursting pressure of 110 lb. per sq. in., or are provided with means to cool the products of combustion as they emerge from the case, thus rendering them incapable of causing ignition. There are two main methods whereby this is accomplished, namely the gaping-flange and the special relief device.

The former is exemplified in the contactor equipment forming Fig. 129. In this, the flange whereby the cover is bolted to the case is made 3 inches wide, and a uniform gap of $\frac{1}{32}$ in. is maintained at the flange by means of spacing washers. Experience has shown this design to be safe for a box of the approximate proportions shown, and its fitness was also demonstrated by a test in an atmosphere of coal-gas and air, which is much more ignitible than a fire-damp mixture. For smaller plant, such as totally enclosed air-break switches of 50 amperes capacity and less, it is sufficient to provide flanges of from 1 to 2 inches in width, which are only roughly machined and are bolted together without spacers.

The second method consists of the provision of an orifice which cools the gas passing through it either by expansion through very finely perforated metal or by straining through the narrow passages between sheet-metal laminae. As a result of a long series of tests with both fire-damp and coal-gas, the author has found that the latter design is safe when the ratio of the total area of the relief passages to the volume of the enclosure is not less than 6 sq. in. per cu. ft. Suitable dimensions for the laminae are $1\frac{1}{4}$ in. wide by 0·015 in. thick, with a space of the same thickness between. The safety of the device is much increased by the addition of a valve outside the orifice, preventing the quick

ingress of the external atmosphere after an explosion inside, and also closing the aperture against the entry of dust and moisture.

As the explosion pressure is much increased by the initial compression of the mixture, it is very important that the interior of the case be not divided into communicating compartments, in one of which the gas may be compressed by an explosion in another. Insulating barriers have been known to produce this effect.

## XX

## ELECTRIC CRANES AND GANTRIES

THE crane is one of the oldest and most familiar of mechanical appliances. It consists of a means for transporting masses from one place to another in the immediate vicinity, and as such provides for the movement of the loads in three directions at right angles to one another, corresponding with the three dimensions of space. In the days when steam was the most effective source of mechanical power, all three motions were performed by the exertions of the one engine, through the medium of appropriate clutches and gearing. To-day, however, the use of a separate motor for each is one of the facilities provided by the adoption of electricity, and this practice is almost universal for all forms of electric crane.

¶ TYPES OF CRANE.—There are few pieces of apparatus that vary so widely in their general form as that under discussion; but all are alike in the provision of the one vertical and the two horizontal movements. Of these the first is of the same nature for all types, and always consists of hoisting; but the others differ in character according to the mechanism by which the motions are carried out, and these in turn depend on the range through which movement is required, and on the nature of the work. The jib-crane is the most typical form, and holds the field for the handling of sea-borne cargoes on ship and wharf and for building construction. It is also much used in the factory, though not as much as in olden days, before the coming of the overhead variety, when heavy loads were transported by passing from one jib to another right down the shop. The horizontal movements consist in this case of a radial one, known as luffing or derricking, effected by altering the angle of the jib; and slewing, or moving it round in a circle. The frequency with which the one crane, of this or any other type, is seen executing all three movements simultaneously and thus securing the maximum of time economy, is a sufficient illustration of the need for three separate motors.

The girder crane is the principal form employed inside a works. In it the hoisting gear is carried on a truck which can move across the space spanned by the girder, while the latter can travel along the building upon rails supported at the top of columns alongside the walls or forming part of the walls themselves. Power is fed to the hoisting and traversing motors on the truck by means of trolley wires above or between the girders; their number may be reduced by adopting 'single-pole' wiring for these motors, the series field of each motor then being permanently connected to a common negative return wire.

Other types are in nearly every case combinations of these two forms. Portal and semi-portal types are usually jib-cranes mounted on gantries

which have both ends, or only one as the case may be, elevated on 'legs'; the other end in the latter case resting on a rail running along the wall of a wharf shed or other building. A hammer-head crane is a horizontal jib upon which runs a hoisting truck very like that used in the girder type. There are numerous other specialized forms, such as charging cranes for steel furnaces, ladle cranes, unloading bridges, and so on; but in spite of the variety, the control principles are practically identical for all.

¶ TYPES OF MOTOR.—On account of the heavy starting torques and frequent acceleration required, series motors are usually employed, D.C. having the advantage over A.C. in that it offers the more convenient

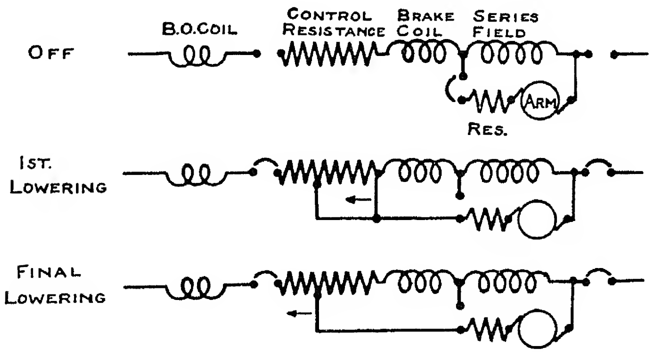



*Fig.* 183. Diagrams of connexions giving scheme for controller shown in Fig. 184.

control of the lowering operation. When A.C. only is available, however, wound-rotor induction motors are a satisfactory substitute.

Drum controllers are generally utilized for motors up to about 100 H.P., and contactor gear for larger capacities; but the automatic features of the latter frequently secure its use for comparatively small equipments. The operator is usually housed in a cab suspended from one end of a girder crane; but small models are often controlled from the floor, and large ones from a cab suspended from the truck itself.

¶ CONTROL GEAR.—The control of the horizontal motions for ordinary types of crane needs little comment. Standard resistance control is the rule, and braking is effected by 'plugging', or reversing the motor through the whole of the resistance. Foot-brakes may also be utilized instead of or in addition to the above.

For the hoisting, however, quite specialized control is employed when D.C. is available. In the first place electric operation holds out special facilities in the shape of sensitive and convenient braking for governing the downward movement of the load; and secondly, creeping speeds are frequently required. A special form of mechanical brake, known as the Weston pattern, is employed for steam cranes, in which the retarding

effect is applied by and is therefore proportional to the actual load. This is not used with electrical working, and in the event of a steam-driven equipment being converted this appliance should be disconnected. Its place is taken by two distinct braking capabilities of the motor itself, while an electrically operated mechanical band- or shoe-brake is keyed directly on to the motor shaft at the commutator end.

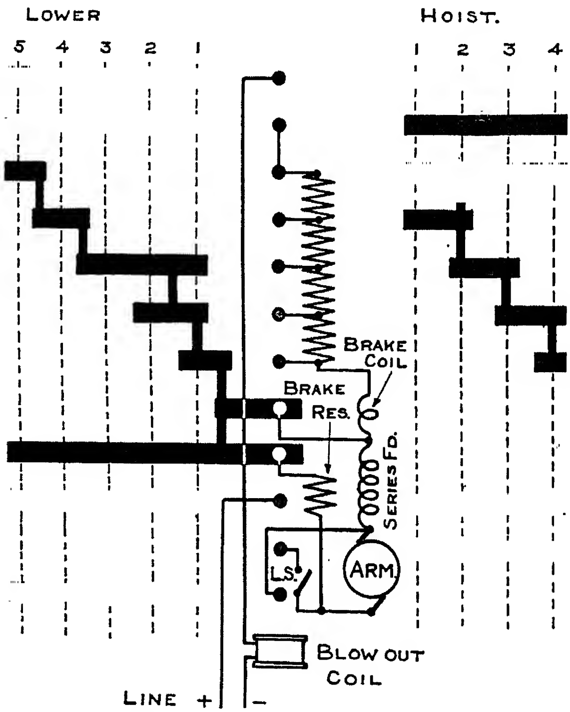



*Fig.* 184. Drum controller for series crane motor giving dynamic braking in the off position and potentiometer braking for lowering.

The retardation in this case is actually applied by a spring or weight, the function of the electro-magnetic gear attached to it being to hold the brake off while the hoisting motor is in action. With D.C. equipments the brake solenoid is nearly always in series with the motor, but for A.C. a shunt connexion is necessary. Either arrangement functions as an emergency appliance holding the load in the event of the power failing; but when the series pattern is applicable it affords a somewhat higher degree of reliability than the other.

The principle of the crane-motor controller, including the application of both simple dynamic and potentiometer braking, is illustrated in the control diagrams forming Figs. 183 and 184. Hoisting is carried out in

the ordinary manner, by switching on the motor with resistance in series, which is gradually cut out in order to accelerate to full speed. Simple dynamic braking is applied for the purpose of stopping the motor when the controller is moved to the 'off' position, by the connexion of the armature in a closed circuit with the series field and a special braking resistance, as in Fig. 184, stage 1. For lowering, the controlling resistance,

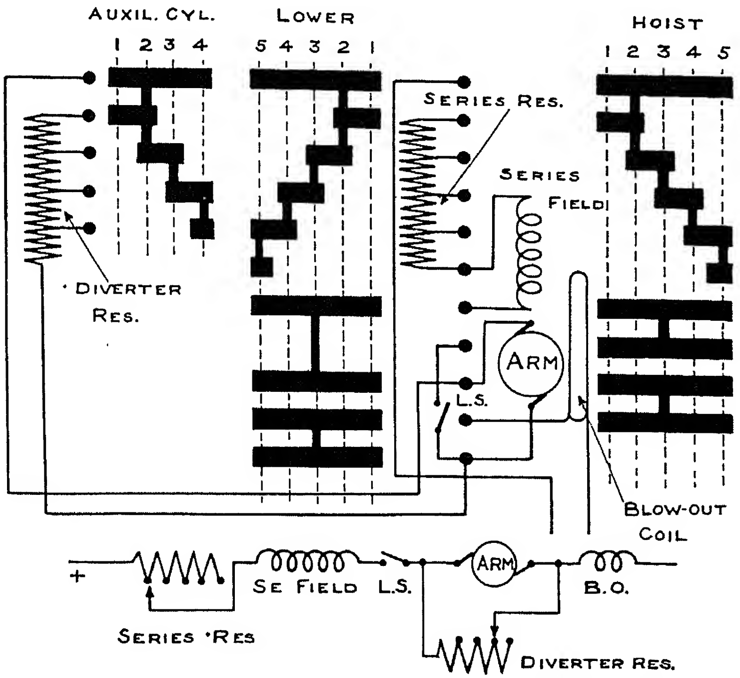
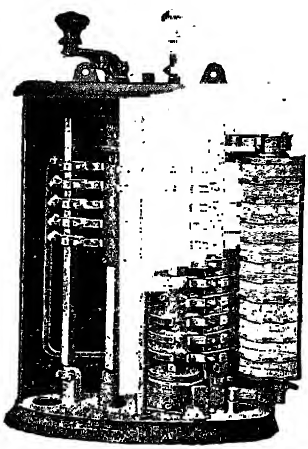



*Fig.* 185. Two-cylinder D.C. controller giving slow motion by diverter resistance.

brake solenoid, and field winding are connected in series across the line, with the armature, still with its braking resistance, shunting the two series windings, the motor being thus endowed with a shunt characteristic. To begin with, part of the main resistance is short-circuited, as shown in stage 2, and the field is strongly energized. The motor therefore tends to rotate at a constant slow speed, drawing power from the line if required to drive down an empty hook, or acting as a generator if the load is heavy. The speed is increased by progressively removing the short circuit across the portion of the controlling resistance, which is now cut into the field circuit. After this the left-hand armature lead (Fig. 183) is moved towards the left, cutting more resistance into the field and out of the armature circuit. At all these points the self-regulating power of the shunt motor adjusts the braking effect to keep the speed

near the desired point, supplying power when this is needed or returning it to the line when there is power to spare. The drum controller shown developed in Fig. 184 is designed to carry out all these connexions.

When finely adjusted slow-motion is required, it is obtained by connecting a 'diverter' resistance across the armature with all or nearly all the controlling resistance also in circuit. This process is shown in the schematic diagram in the lower part of Fig. 185. It may be carried out as a preliminary to the usual acceleration of an ordinary single-drum controller, the first two steps in either direction being thus utilized and giving speeds down to 10 per cent. of normal; but for several reasons a separate small drum for cutting in and out the diverting resistance is an advantage, and is used in the B.T.H. design shown in this figure and the next. For one thing the creeping speed is not employed until it is actually required, there being no necessity to run through these extra slow positions every time the motor is accelerated or brought to rest. A certain amount of arcing is thus obviated in the latter case. Finer speed adjustment is also possible by the combination of several steps on the auxiliary with two on the main cylinder. In the example shown developed in the figure there are four steps on the auxiliary unit, rendering eight slow-speed graduations available. This type of control is particularly useful for foundries, where the removal of patterns from moulds must be carried out with the greatest care. A view of the controller, opened up for inspection, is given in Fig. 186.



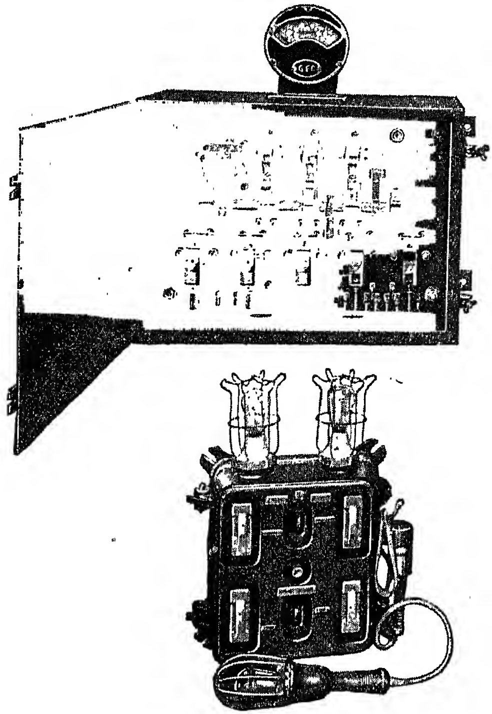
*British Thomson-Houston Co., Ltd.*

*Fig.* 186. Double-drum controller for creeping speeds, with cover removed and case opened. Note blow-out coil at foot of main drum, and mechanical interlock and star-wheels at top of both drums.

In such a case as the above the two cylinders must be interlocked to obviate trouble through incorrect operation. It must be impossible to bring the diverter into use until the main cylinder is returned to the 'off' position. After the former has been brought into action the motion of the latter must be restricted to the first two steps, of which the second is only needed for loads heavier than the normal. As the auxiliary cylinder is not designed to rupture the circuit, it must be impossible to move it to its off position until after the whole has been disconnected by the main cylinder.

The control of A.C. motors is similar to the D.C. case as regards the carrying out of positive work, speed variation being effected by resistance control in the wound-rotor circuit. The practicable speed range is, however, not so great as with D.C., and, apart from plugging and power lowering at slightly above synchronous speed, braking by means

of the motor cannot be effected. Extended use has to be made of the electro-magnetic brake, supplemented by a foot-operated or other mechanical type. It is therefore often the practice, where any considerable number of cranes have to be operated in the same establishment, to instal a converting plant and to employ D.C. motors, at any rate



*General Electric Co., Ltd.*

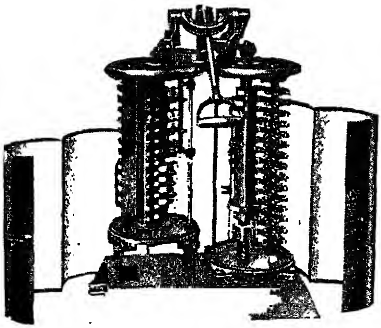
*Fig.* 187. Crane protective panels.

when a wide speed variation is required and a varying load has to be dealt with.

¶ LIMIT SWITCHES.—To guard against carelessness on the part of the operator, risk of over-travel is definitely obviated, especially in the case of the hoisting motion. This is effected by means of limit switches, the position of which for hoisting controllers is indicated in Figs. 184 and 185. A compulsory stop is most required in preventing the hook or block from being pulled up against the jib or truck, for there will often be a minimum of clearance here. For drum controllers the limit switch is usually located in the main circuit, cutting off the current from the motor and the solenoid brake and enabling the latter to come into instant

operation. When contactor gear is employed the limit switch will generally interrupt the auxiliary circuit; but since over-travel may be due to the sticking of a contactor it is the safest plan for a master contactor or circuit breaker to be opened in addition to the line-contactors. These limit switches are usually tripped by dogs moved by a feed screw rotating with the crane shaft.

¶ PROTECTIVE PANELS.—Protection against overload is now generally provided for drum-controlled crane motors by means of what are known as Crane Protective Panels, an example of which, together with a separate pilot panel, is illustrated in Fig. 187. The chief component of these is a two-pole or three-phase contactor through which passes the power supply for all the motors of the crane. The excitation for this master contactor may be interrupted by a number of time-element overload relays, the coils of which are connected in the motor leads, there being usually one for each machine and one for the common return. An overload in any motor or in the system generally can thus open the contactor; and it can be at once closed by the operator in some convenient manner, restoring the power supply. If the relays are of the electrically reset pattern, they can be dealt with by a special contact on the controller which is closed as soon as it is moved to the 'off' position. Hand-reset relays need to be located where they are easily accessible to the operator. The restoration of either form takes far less time than with a fuse, which might cause a serious delay at a critical juncture.



*General Electric Co., Ltd.*

*Fig.* 188. Sympathetic levers for crane control.

It is customary to fit a switch or plug which can also de-energize the master contactor. This is provided with means for locking it in the open position, to enable repairs to be effected on the crane equipment with safety. A socket for plugging in an inspection lamp is also fitted in the pilot panel shown in the figure, as well as two pilot lamps. This equipment is so interlocked electrically that the pilot lamps are lit when the master contactor is closed, but the hand lamp can only be used when the contactor is open.

¶ CONTROLLER LEVERS.—Since three different controllers have to be handled simultaneously by the one operator, a considerable advantage is gained by providing for two of these to be actuated by means of the same lever. The usual arrangement is to associate them in such a way that a horizontal movement of the handle moves the one cylinder and a vertical one the other. An example of such a mechanism is shown in Fig. 188.

These handles enable what is known as 'sympathetic control' to be carried out, the principle of which is that the operator moves the appropriate handle in the direction towards which he desires the load to go. Thus, if the handle of the controller shown in the figure be raised vertically, the load is hoisted; while if it be moved to the right the crane slews in this direction. Pushing the other lever forward causes the jib to

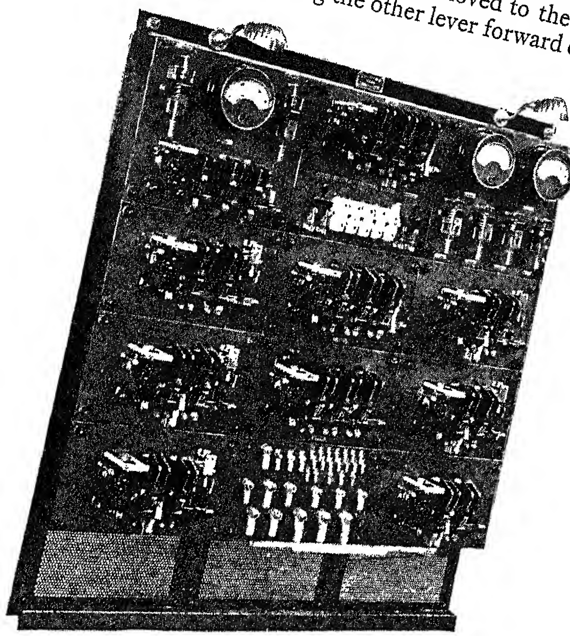


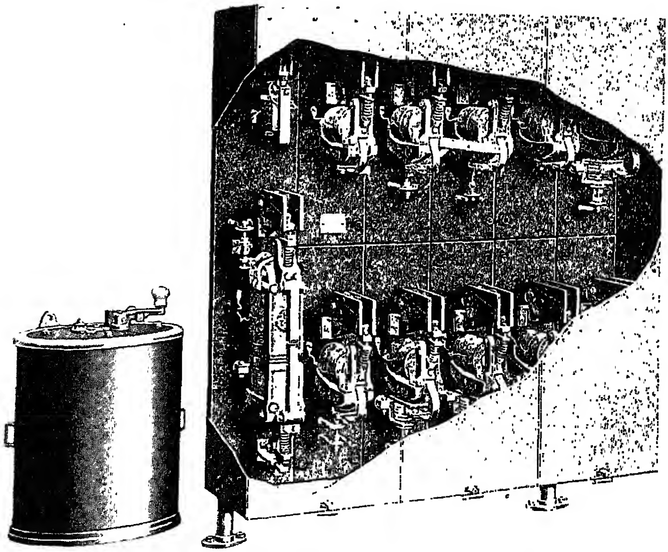
*Fig. 189.* Contactor-control gear for A.C. 120 H.P. hoisting motor. *General Electric Co., Ltd.*

derrick forward, and so on. It will be seen that it is an easy matter to operate all three motions simultaneously, while the simplicity of the control permits the attendant to concentrate his attention upon the load.

¶ CONTACTOR CONTROLLERS.—As has already been stated, contactor gear is employed for equipments exceeding about 100 H.P., and for smaller installations when automatic control is especially desired. The circuits for the contactor schemes are, however, very similar to those already given for manual controllers, practically the only difference being the use of fewer accelerating steps. Their advantages are uniformity of operation, resulting in economy of time and greater freedom from interruption, and greater durability. They are, however, more costly, and they lack the great compactness of the drum controllers, a quality that

especially suits these for such a confined space as a cab. Frequency of service is a consideration that often turns the scale in favour of contactor gear.

An example of the latter is shown in Fig. 189, being the control equipment for the 120 H.P. hoisting motor of a coal unloading jib-crane of the full portal type. This works in conjunction with seven other similar cranes and two belt conveyors, the last named having a total capacity of 2,000 tons per hour. Each crane operates a $3\frac{1}{2}$-ton



*British Thomson-Houston Co., Ltd.*

*Fig.* 190. D.C. contactor controller for crane, with cover broken away; also master controller. The double-throw dynamic brake contactor is on the left.

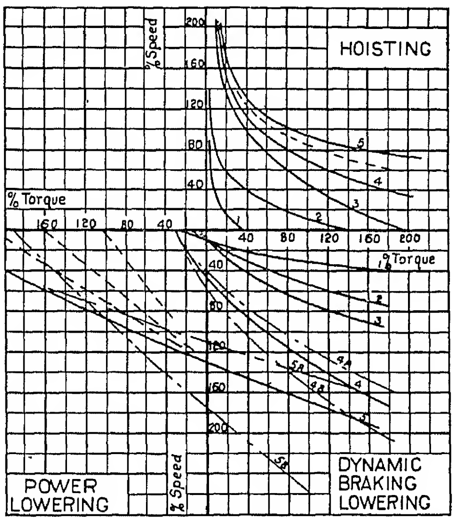
grab, and has three motors in addition to that for hoisting, namely one of 70 H.P. for derricking (or luffing), one of 20 H.P. for slewing, and one of 10 H.P. for travelling.

The electric apparatus is designed for A.C., and the control gear thus consists simply of reversing line-contactors (occupying the middle of the board) and current-limit accelerating units, of which there are six. The former are three-phase, with the usual mechanical interlock between them; while the latter, situated three on either side of the line units, are as usual two-pole. These have individual current-limit relays associated with them, which may be seen at the right of each above the rocker shaft.

The other motors are governed by means of drum controllers, but are protected against overload by the time-element relays on the top left- and right-hand panels, which open the three-phase master contactor on the top middle panel if an excessive current flows in any lead.

The triple-pole contactor on the top left-hand panel controls the solenoid brake on the grab winding-drum, and is fitted with a retaining contact to give a no-volt release feature. The knife switches are for the pilot and inspection lamps, and the fuses are for these and the operating coil circuits.

A representative D.C. crane equipment is illustrated in Fig. 190, comprising the control gear, with master controller, for the 40 H.P., 220-volt hoist motor of a hot-metal crane. The sheet steel containing




*British Thomson-Houston Co., Ltd.*

*Fig.* 191. Typical characteristic curves of installation such as is shown in Fig. 190.

case appropriate for this purpose is well shown in the figure, while the five accelerating contactors with series relays in the bottom row, and the reversing and circuit-breaking line-contactors above them are also clearly visible.

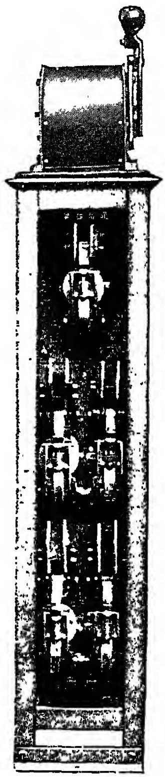
The large double-throw dynamic braking contactor on the left is perhaps the most interesting feature. This particular function is of special importance with hot-metal cranes, and failure would be attended with unusually serious results. The robust construction of the contactor concerned is therefore worthy of note. It comprises a normally open and a normally closed unit mechanically interlocked, but electrically insulated one from the other. The combination is 'set' by means of the upper or shunt coil, which closes the upper contacts, the series coil only carrying current during braking and then 'sealing' the lower contacts.

The characteristics of such an installation as is described above are

given in detail in the curves forming Fig. 191, which show the relationship between speed and torque, both expressed as a percentage of normal full-load values, for hoisting and potentiometer braking conditions. Each curve is numbered to indicate the position on the controller upon which that particular characteristic is given.

For hoisting both torque and speed are positive, and the interpretation of the curves for the five forward positions of the handle is quite simple. When, for example, the third hoisting point is employed, it is seen that 80 per cent. of normal full-load torque is given at 60 per cent. of normal full-load speed. For lowering speeds, the curves below the horizontal axis are interpreted in the same manner, and their position with regard to the vertical axis shows the conditions under which the load gives up energy as its descent is retarded, or requires the application of power to drive it down. The fifth braking point may be taken as an illustration, showing that 80 per cent. of positive torque is produced at 160 per cent. braking speed; but that when the load is only sufficient to develop 96 per cent. of full speed in the reverse direction, a negative torque of 80 per cent. of full-load value has to be supplied from the line to drive it down. Zero torque occurs at 130 per cent. of normal speed, the load now being merely able to rotate the motor without requiring either dynamic braking or external power supply.

The chain dotted lines on the diagram, marked 4A, 4B, 5A, and 5B, show speed adjustments that can be made on points 4 and 5 by the use of extra resistance. The dotted lines on the left-hand side indicate automatic, as distinct from hand-controlled, points.



*General Electric Co., Ltd.*

*Fig.* 192. Lifting magnet control gear.

¶ CONTROL OF LIFTING MAGNETS.—The problem of controlling an electro-magnet is not quite as simple as it would seem to be at first sight, on account of two rather troublesome characteristics. In the first place, the inductive potential kick across the coil and the switch contacts would produce a considerable arc if the circuit were broken without special precautions, and would seriously strain the insulation. Secondly, even when the energizing current has ceased, much of the magnetism may still persist, especially if the load forms an efficient 'keeper' circuit for the magnet poles.

To deal with the former difficulty a non-inductive resistance is always switched across the magnet terminals before the exciting circuit is

broken, having a magnitude about equal to that of the magnet coil itself. Thus the current flowing in the inductive winding is not interrupted, but expends itself in heating the resistance. Since any peak voltage that may occur is a multiple of that supplied from the line, this is therefore usually fixed at a low value, such as 110 or 220 volts.

For dealing with the remanent or residual magnetism the control gear is designed to reverse the applied voltage for about a second before

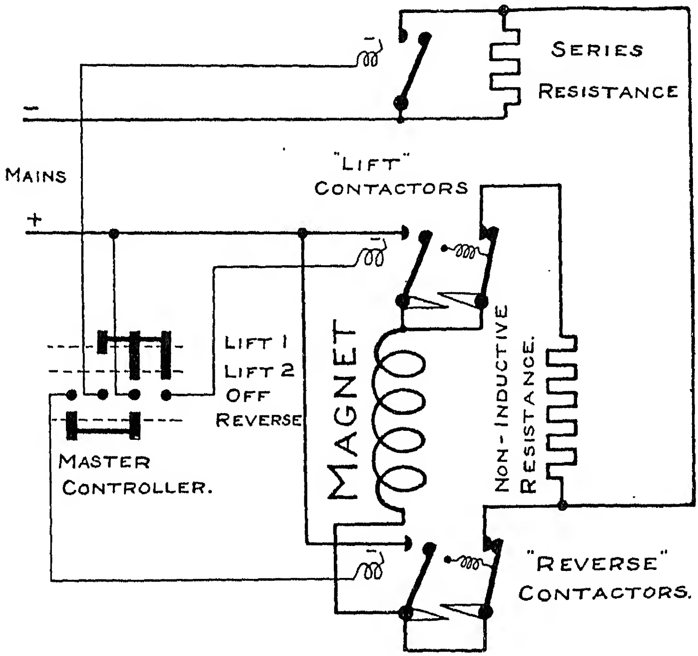



*Fig.* 192A. Control of lifting magnet.

disconnexion, thereby bringing about the release of the load with certainty and with a minimum of delay.

These functions are carried out by means of the contactor gear shown in Fig. 192. There are five single-pole contactors in a sheet-iron pillar, with the resistors of copper-nickel wire at the back of the slate panels. The master controller may be mounted either on top of the pillar, or separately in any convenient position. The connexions of the whole installation are given in Fig. 192A.

Of the five contactors in the pillar the top one is for the purpose of short-circuiting a series resistance; and reference to the master-controller connexions will show that this is only done for the final 'lift' position, the first 'lift' and the 'reverse' both being accomplished with the resistance in circuit. The right-hand units of the other two

pairs have no coil, and each is forcibly opened against the action of a spring just after its neighbour closes. They consequently close just before the other opens in each case and thus cut the non-inductive resistance into circuit before either circuit is interrupted. The spring guide associated with the operating handle is so designed at the upper end that the contacts cannot be left in the reverse position.

¶ CONTROL OF GRAB-BUCKETS.—When loose materials such as coal, ore, or foundry sand are to be handled, use is made of the Priestman grab-bucket or of some similar device. There are several alternative methods of controlling these, varying in the convenience of manipulation and in the elaboration of the control apparatus, both mechanical and electrical.

To begin with, there are two principal forms of grab, depending on whether they are designed to be operated by one or by two chains. The former needs no addition to the usual crane equipment, the chain passing over the single drum as with other loads ; but a ring is suspended by independent wire ropes or chains from the jib or trolley so that it encircles the hoist chain and can engage with a hook at the top of the grab, its height being that at which unloading is desired. The 'stirrup' frame of the grab thus being suspended, the cross-beam supporting the pivots of the jaws is lowered by paying out chain until the grab is wide open. A spherical button, fixed upon the chain above the grab, has descended sufficiently in the full open position to engage with the under-side of a tumbler, which opens the hook after the chain has been hoisted up through a few inches. The grab can now be lowered to pick up a fresh load. It will be seen that a certain amount of head-room is taken up by the ring and its suspension, and also that there is a subsidiary movement to be gone through in addition to the ordinary routine of hoisting and lowering. Further, unloading can only take place at a fixed height, and in the event of the grab seizing upon some fixed object, for example below water, operations have to be suspended while special means are employed for freeing the jaws.

The use of an additional small chain supporting the stirrup removes these drawbacks, but requires a second drum for its reception. In the simplest arrangement the latter is not power-driven, but is rotated by a coiled spring, usually by means of gearing, the tension being sufficient to keep the chain taut at all positions. The auxiliary drum is provided with a simple mechanical or electro-mechanical brake, which has only to be applied while the main drum is lowering to open the grab at any desired height. The jaws remain opened during the subsequent descent until hoisting begins, when they are pulled downwards and inwards by the hoist chain. This type of drum is supplied in detachable form, ready to apply to existing single-drum cranes.

A maximum of convenience is afforded by the provision of a second motor-driven barrel with independent control gear, of the same pattern as employed for the main drum.

¶ UNLOADING BRIDGES.—An unloading bridge is a large gantry crane with the legs relatively wide apart and provided with motor-driven wheels for longitudinal travel. A trolley, usually bearing the control cab with it, runs backwards and forwards along the bridge rails, which in most cases project upon a cantilever beyond at least one support, in order to pick up the load directly from the hold of a vessel. Grab-buckets are usually operated from the trolley, and the duty is in general so heavy that contactor gear is the rule.

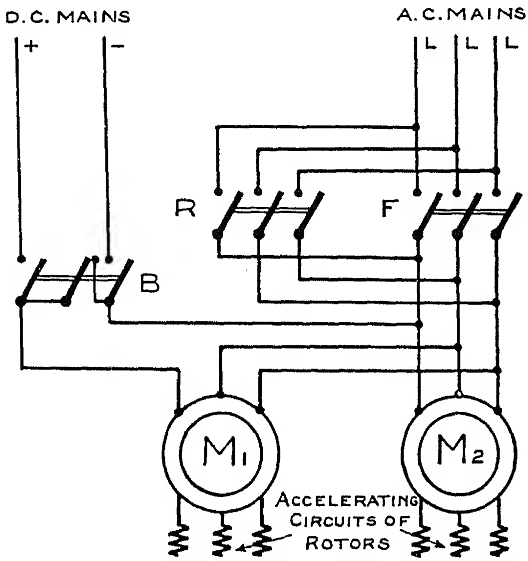



*Fig.* 193. Diagram of connexions for stators of two A.C. motors to give dynamic braking with D.C.

The control of the hoist has already been sufficiently described as regards the D.C. form. So important, however, is dynamic braking with these large equipments that, when A.C. has to be employed, a special small low-voltage motor-generator is often installed to excite the stator of the motor or motors with D.C. for lowering purposes. The connexions for such a scheme are given in Fig. 193, in which two motors are shown with their stators connected in parallel for power operation but in series for D.C. braking. It is unfortunately not possible to utilize the three-phase windings very efficiently for D.C. excitation, as two phases in each with their windings at 120° have to be excited in parallel. Braking is hence not quite so effective as with D.C. The connexions for the simpler case of a single motor can be deduced from the above.

For driving the trolley two motors are commonly used, which are frequently controlled on the series-parallel system ; but the armatures

may also be connected permanently in parallel and the fields in series. In the latter case it is good practice to provide separate reversing contacts for each. Both plain dynamic and potentiometer braking are employed, although an air-brake is a common alternative. For A.C. working the same arrangement as is indicated in Figs. 130 and 189 may be used.

The bridge is generally driven by one or even two motors on each leg, and for long bridges these are operated from two separate controllers, but have a relay which disconnects the driving gear on one side if it leads the other by more than a certain small amount. For smaller structures one motor may be arranged to drive both trucks by means of bevel gearing. The inertia effect is much less than with the rapidly moving trolley, and dynamic braking is not necessary. Shunt-wound solenoid brakes are in order for independent drives, and a mechanical foot-brake for the single motor arrangements.

¶ General Design.—For all components of cranes a high degree of robustness is essential. Practice as regards both motors and control gear has been based on traction methods, while mill-type motors are used for the heavier classes of service. The size of the electrical apparatus is, however, reduced by the intermittent nature of the work, a half-hour rating being standard for ordinary duty and three-quarters to one hour for the severest cases, such as grabbing and other work which involves uninterrupted service at full load.

It seems probable that the further development of the Boucherôt double-deck squirrel-cage motor will enable this high-torque variety to take its place as an alternative to the wound-rotor type for many purposes, introducing a great simplification of the A.C. control gear.

## XXI

## MACHINE-TOOL CONTROL

THE individual operation of machine tools forms one of the most interesting departments of motor control. So varied are the cycles of movement, rates of speed and acceleration, varieties of motion, requirements as to means of regulation and position of handle or button, and the other conditions under which the different types of work are carried out, that machine-tool control can be truthfully said to stress the resources of electrical engineering to the utmost, and to include almost every device known to the art. At the same time the improvements resulting from the application of efficient control methods are so marked that the designer may well feel himself repaid for his labours by a realization of the immediate advantages they have conferred.

It will be in order to devote a few preliminary words to the general design of an electrically operated machine tool. To begin with, three different components are involved, namely the machine itself, the motor, and the control gear, and these should be amalgamated to form a complete, self-contained, robust, and convenient unit. Now such a process is not as a rule carried out in one step. For example, the electric tramcar is formed by the union of the motor, control gear, and vehicle ; and in the beginning the two former were merely attached to the last, which preserved its original horse-drawn form. It was not, however, until the components were merged together, and the whole designed as a co-ordinated unit, that satisfactory results were possible.

The same is true of the electrically driven machine, which is only too often seen in the first condition, development having been discontinued at the most important stage. In fact, it is most common to find individual drive applied by the separate location of the three pieces of apparatus, none being specially adapted for working together. For example, a machine tool of the usual pattern intended for belt drive will be belted to a countershaft driven by a motor fixed somewhere on the floor or walls, and an ordinary hand starter will be situated somewhere else, usually in a very inconvenient place. It is even not considered peculiar by some shop authorities to station a labourer at the starter of certain machines, for the sole purpose of operating it when the machinist requires a change in the running of the motor. With an arrangement such as is described above, it will be seen that operation has not been improved to any extent as a result of the electrification, while the care that has to be observed in working the starter, and sometimes the additional man-power required by it, are extra drawbacks not possessed by the mechanical drive.

In contrast to this primitive and unconsidered scheme, the ideal procedure would consist in designing the electrically driven and controlled machine as a harmonious unit, with the motor and control gear

forming integral parts of the whole, and with the control handles situated in the most convenient positions for the operator. These would in general be located among the other levers effecting the purely mechanical control, and should require no greater care in their operation than the latter. It should be remembered that when a machinist, man or woman, is engaged on remunerative piecework, all motions are apt to be executed at express speed ; and the existence of one control that has to be nursed for fear of a shutdown is a state of things as defective as it is unnecessary.

¶ TYPES OF ELECTRIC CONTROL.—The majority of machine tools can be grouped under the following heads :

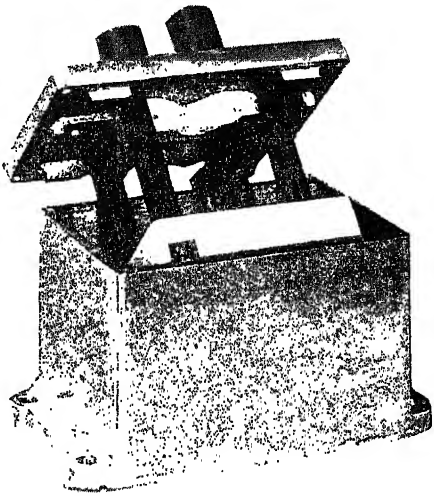
(1) Small-power tools, possessing a motor of about 1 H.P. or less. These would be completely controlled by a plain switch.
(2) Those requiring moderate power, such as 5 or 10 H.P., without speed control, for an infrequent auxiliary function such as the raising and lowering of the tool-bearing cross-bar of a boring-mill or planer. A simple drum switch usually suffices for these.
(3) Machines of moderate horse-power, such as many types of lathe, small shaping-machines, &c., that need infrequent starting and no reversing or braking, and usually no speed control. Automatic control is optional but to be preferred.
(4) Machines of moderate horse-power, such as radial drillers and screwing machines, that require repeated starting and reversing and must be lever-controlled, but do not call for special braking or speed regulation. Contactors must be employed for these.
(5) Machines of fairly large horse-power, such as boring-mills, that require to be started infrequently in one direction only, but must be capable of being inched both forward and back for setting up. Speed control and braking may also be required. Automatic control is indicated for these.
(6) Machines such as wheel-lathes requiring ordinary 'lathe' control, except that there must be provision for slowing down over given portions of the revolution ; requiring automatic control.
(7) Reciprocating machine tools of fairly large power, such as planers, slotters, shapers, &c., that require reversal of the motor at the beginning and end of each stroke, with dynamic braking, rapid acceleration, quick return and quick motion when 'cutting air', adjustable speed at all parts of the cycle, and inching both ways for setting up. This class demands the most advanced form of contactor or Ward-Leonard gear.

## ¶ EXAMPLES OF ELECTRIC OPERATION AND CONTROL

(1) SMALL TOOLS.—There are numerous small bench and hand machines, such as small sensitive drillers, portable drills, &c., which can be driven by a fractional horse-power shunt, series or induction motor, and can be stopped and started by the simple opening and closing of a switch. The loom motors described in Chap. XVI, with

their small drum switches, in reality belong to this class; but for an engineering works the push switch is the most convenient form of control gear.

A good example is shown in Fig. 194, consisting of a robust pattern with two breaks per pole and a capacity of as much as 10 amperes at 250 volts. The moving contacts are attached to the one stem, which is urged to the off position by a compression spring in the hollow piston. When it is fully depressed a horizontal flat latching bar sliding against the under-side of the top plate moves into a nick in the contact stem



*General Electric Co., Ltd.*

*Fig.* 194. On-and-off push switch.

and holds the switch closed. To open the contacts the other piston is pressed, and this terminates in an inclined edge which forces the latching bar back against the pressure of a flat spring, permitting the contact post to rise quickly.

This model is suitable for both stationary and portable drillers, but was actually designed in the first place for the latter, which possess series motors for either D.C. or A.C. working. For the smaller drillers an even simpler device is satisfactory, consisting of a pair of plain butt contacts that are pressed together by the closing of the operator's hand upon the handle of the tool. No quick break is needed for the small currents concerned; and the motors are not large enough to develop an unsafe speed when unloaded, in spite of their series winding. Consequently the design of this driller, though extremely simple, is none the less sound.

The above form of push switch may be endowed with extended functions without any great increase in elaboration. By the addition

of a small shunt solenoid acting on the latching bar, a no-volt release is added. A resistance step may be inserted for larger motors with shunt excitation by the provision of an additional 'spring-return' piston, that removes a short circuit from the resistance when it is depressed together with the starting switch, and reapplies the shorting connexion when the pressure is removed. Speed regulation in any number of steps may be arranged by adding a further series of pushes, each of which cuts some part of a resistance into the field circuit. The separate

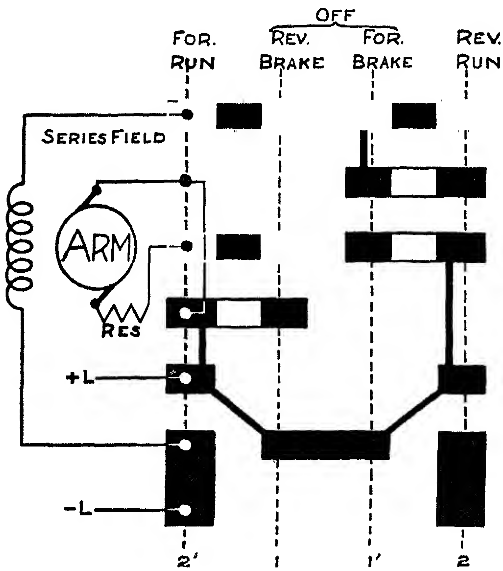



*Fig.* 195. Reversing drum controller with dynamic braking for series auxiliary motors.

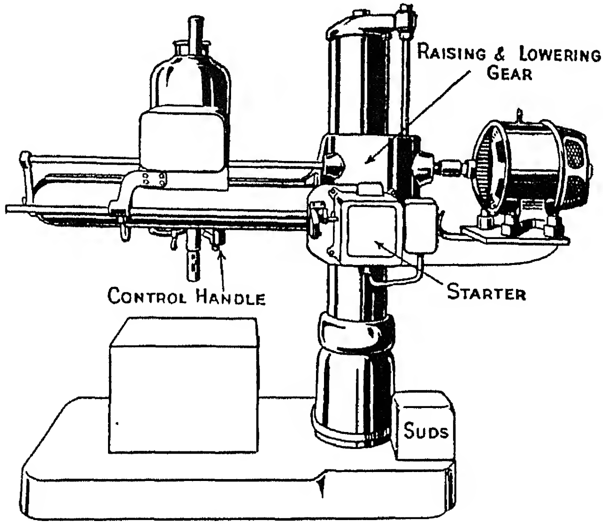
latching bar in this case permits only one push to be depressed at a time, and no resistance to be inserted in the field at starting.

(2) Auxiliary Motors.—The motors employed to raise and lower large radial drill-arms, cross-bars of planers or boring-mills, &c., are practically always series motors of up to 10 H.P. in size. They are required infrequently, when the work is being set up, and for only short periods of about a minute at most. Consequently heating and efficiency are unimportant factors. The armature conductors can be of comparatively small section and high resistance, and the motors are thus extremely easy to start.

It is well known that the standard series type up to a rating of about 8 H.P. may be switched straight on to the line without risk or excessively abrupt starting, and these models with their higher resistance will be even more adapted for simple switching. A plain reversing drum

switch, mounted on the machine column, is suitable for the purpose. If an ordinary low-resistance armature is fitted there is no objection to the connexion of a small external resistance permanently in the armature circuit for the larger motors.

A brake is sometimes an advantage to stop the motor definitely when the cross-bar or arm has reached its final position. Since the last portion of the reduction gearing consists of a fairly fine-pitched screw, there is no need for a holding brake, and a solenoid pattern would in






*Alfred Herbert, Ltd*

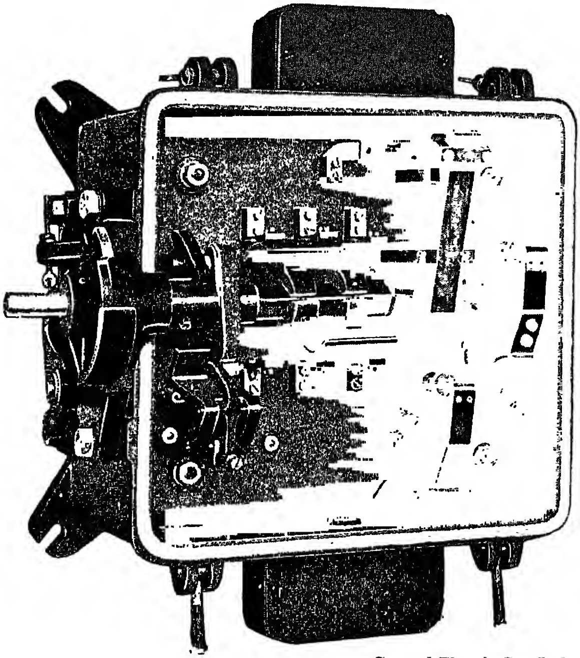
*Fig.* 196. **Electrically operated radial driller.**

most cases be unduly expensive. Dynamic braking is therefore the most appropriate, and may be brought about by reversing the motor connexions and short-circuiting its terminals, the external resistance, if any, being included in the circuit.

The diagram forming Fig. 195 illustrates a simple drum switch giving running positions, 2, 2′, forward and reverse, when the handle is moved to the limits of its travel, a ‘ drift ’ position in the middle, when the armature is disconnected, and brake positions when the handle is moved a step farther, to 1 or 1′. It should be noted that as the series motor requires reversal in order to generate without changing its direction of rotation, the passing from say 2′ to 1, which merely applies the short circuit, does not cause braking of any power. If, however, the series field is not included in the circuit, a certain amount of braking is available due to the residual magnetism.

The control of squirrel-cage motors for the above purpose presents no difficulty, but dynamic braking is not practicable.

(3) LATHE MOTORS.—Engine, capstan, or automatic lathes are usua driven, when an individual arrangement is adopted, by motors situat over the headstock, a foundation plate being provided there by ma makers as standard practice. No speed control is usually require though this should form a useful addition, and shunt or squirrel-ca motors are employed. The control lever should be located on t saddle near the tool holder, and the motion transmitted to the fix



*General Electric Co., Ltd.*

*Fig.* 197. Automatic reversing starter for machine tools.

switch or controller by a horizontal 'spline' shaft running parall with the bed; or push-button operation may be used.

The older method of control is by a drum switch, mounted hori zontally at the end of the spline shaft at the headstock end of the bec Squirrel-cage motors would usually require a plain switch in tha position, or at most a star-delta or resistance starter, and hand control i satisfactory. For D.C. motor, however, a small standard contacto starter is to be preferred, and is nowadays justified by the low price a which such apparatus can be obtained. The great advantage of th latter is that no care need be exercised in throwing over the lever, a with the manual starter. Two or three 10-ampere or 25-ampere con tactors at most would be required, with the usual current-limit accelera tion. Wheel lathes are treated separately in Section 6.

The simplest type of automatic control gear is the time-element starter, in which the circuit is made, and the starting resistances are gradually cut out, by means of a moving contact operated by a solenoid and governed by a dash-pot. This form of acceleration is particularly useful for machines, such as large coil-winding lathes, that have to be started very smoothly at practically no load.

(4) Reversible Drillers.—A machine intended for tapping or screwing must be able to accelerate very quickly in the forward direction for cutting the thread, and reverse equally quickly when this is done for the purpose of withdrawing the tool. By far the best way to control the

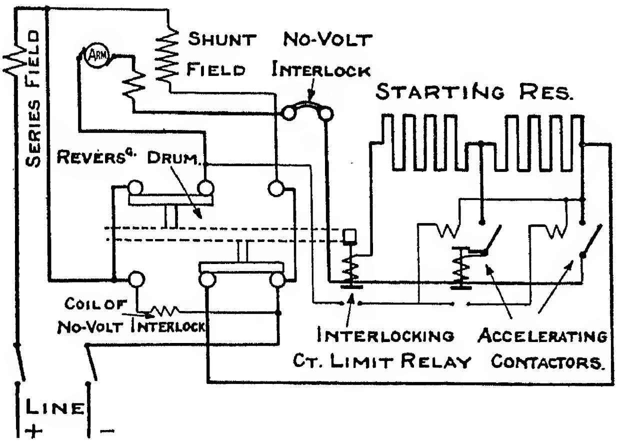



*Fig.* 198. Diagram of connexion for automatic control gear for 5 to 8 H.P. reversible driller.

movement is by means of a lever at the drill-head, capable of being manipulated as fast as the operator wishes. A radial driller intended for such work is shown in Fig. 196, and forms a particularly good example of the correlated design of an electrically operated machine tool. Not only is the motor situated upon the machine where it is out of the way and not liable to receive unfair treatment, and where it is able to drive both the drill-spindle and the raising and lowering gear for the radial arm as directly as possible and with a minimum of intervening gearing, but it also does additional duty as a counterweight for the arm and drill-head. The reversing starter is also placed to advantage, and is operated from the control lever at the front of the drill-head through mitre-gearing. A standard compound or wound-induction motor is used for this type of service.

For the starter an automatic equipment comprising four line contactors for reversing and two accelerating contactors might be used, the line units being operated by means of a reversing master switch moved by the control lever. A much simpler but quite adequate

scheme, designed by the author for this driller, is shown in Fig. 1 (diagrammatically in Fig. 198). Here the line switching and reversi is entirely effected by a drum type of switch connected to the lev through a snap-action device, the object of which is to prevent t contacts from coming to rest anywhere but in the full-on or full- positions. A current-limit relay is associated with the shaft of th switch just as is customary with line contactors when they are employe and brings about the closing of the first accelerating contactor as so as the current peak, due to the closing of the drum switch, has fall to a safe value. A second relay and contactor complete the accelerati in the usual manner. A no-volt protective device is also interlock with the drum-shaft, and may be seen at its right-hand extremit With this apparatus it is possible to jerk the control lever repeated backwards and forwards from full ahead to full reverse without causi a sufficient over-current to damage any part of the equipment or to ri melting the fuse. It will be observed that the motor is brought to re upon reversal by ' plugging '. For A.C. installations the same type control gear is appropriate, but one accelerating contactor is nc sufficient.

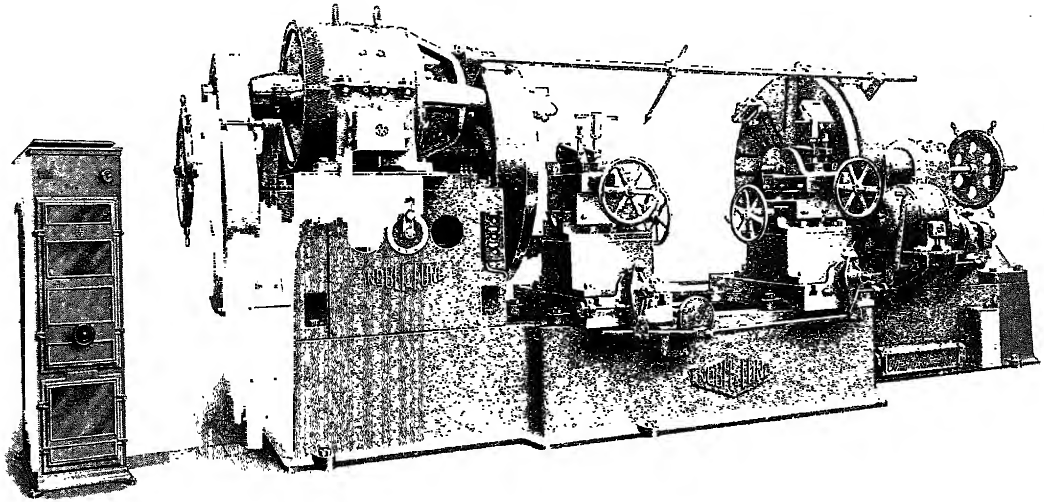
(5) Boring-mills.—Shunt motors of up to about 25 H.P. are mc suitable for boring mills, and similar large machine-tools that rota for long periods in the one direction, but are required to inch both wa for setting up. Upon A.C. circuits a wound-rotor machine would gi equally satisfactory service, except when speed control and dynam braking are asked for. The control gear is housed in a pedestal, or a steel case mounted on some part of the machine frame, and consis of a reversing contactor starter, usually with three accelerating unit operated by Start, Stop, Inch Forward, and Inch Backward pus buttons, exactly as described in Chap. XIV and shown in Fig. 139. N only are these buttons mounted on the control case or other ma operating station, but duplicates are fitted at the tool posts and in a other localities from which it may be desired to start, stop, or inch t motor.

When speed variation is called for it may be provided by the inclusi of a field rheostat in the control case with means to prevent the mot from being started up with the field weakened. The vibrating relay the most convenient means for accomplishing this.

Dynamic braking is a convenience when inching is being carried o as it enables the moving of the table by any desired amount to quickly and accurately effected. It may be brought about by mea of an additional contactor which connects a resistance across t armature terminals when all four line-contactors are fully open ; special double-throw line units may be used.

Large boring-mills may be equipped with reciprocating control for planers, if it is desired that they shall make only a part of a revol tion and then quickly return to the beginning of the cut.

(6) Wheel Lathes.—The peculiarity of wheel-lathe control is th



*British Thomson-Houston Co., Ltd.*

*Fig.* 199. Wheel lathe, showing motor, contactor pillar, and triple push switch.

provision must be made for a comparatively fast speed over most of the revolution of the work, and also for a much slower travel over a certain restricted portion. This is required when a wheel-tread is being re-turned, since there are frequently 'hard spots' where much slower cutting is necessary. The same feature is also desired when the tool is at work upon a crank or similar part for a fraction of the stroke, but 'cuts air' for the remainder.

A simple method for furnishing the double speed is to employ a motor with the requisite speed ratio (e.g. 2 : 1 or 3 : 1), together with a field rheostat which can be short-circuited by a small contactor when slow speed is desired. A push-button is frequently located on the headstock or saddle whereby the operator may close this contactor, or even directly short-circuit the resistance, when the 'hard spot' comes round.

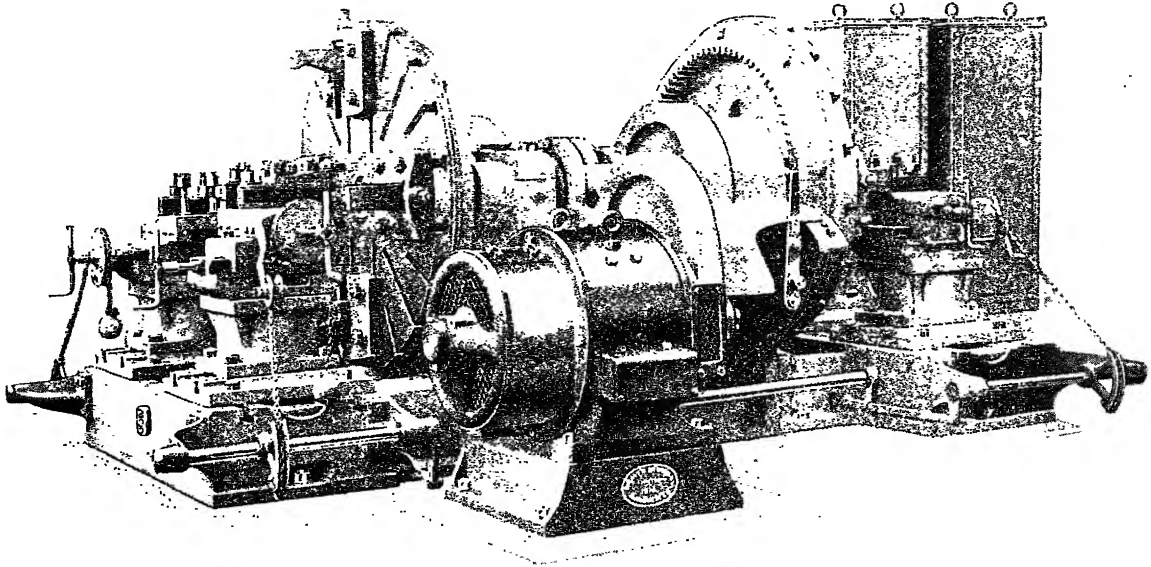
There is, however, no objection to armature speed control for such a purpose as this, where the intention is to ease the stress on the cutting edge, and a somewhat faster speed for the less serious hard spots is therefore in order. This method is employed in the equipment shown in Fig. 199, where resistance sufficient to reduce the speed to 50 per cent. of that with full field may be cut into the armature circuit. The push-buttons may be seen on the headstock near the operator, and are labelled 'Start', 'Stop', and 'Slow'. Dynamic braking is included and inching if desired, and a field accelerating relay is fitted.

The example in the figure comprises a 66 in. heavy-duty wheel lathe by Noble and Lund, with a 40 H.P. non-reversing compound motor for driving the headstock, running at 300-900 r.p.m.; and a $7\frac{1}{2}$ H.P. shunt motor for operating the tailstock. For the latter, a drum controller and starting resistance are located just below and in front of the motor; while the main drive is controlled by contactor gear housed in the pillar situated on the left, and operated by the push-buttons.

A somewhat different installation is shown in Fig. 199A, being a double tyre-boring lathe by Craven Bros., Ltd., driven by two 15 H.P., 450–900 revs. per min. Metropolitan-Vickers D.C. motors, each operated by a separate control pillar and push-buttons. One set of the latter may be seen on the machine base at the extreme left of the photograph.

For an A.C. equipment a wound rotor would have to be employed, into circuit with which resistance would be cut for the slow speed. Since the greatest torque is needed at such portions of the work, a squirrel-cage motor with voltage control would not be at all suitable.

(7) Planers, Shapers, and Slotters.—The operation of planers has presented the most intricate problem in connexion with machine-tool control. It involves the rapid accelerating of a heavy mass for the cutting stroke, halting it exactly at the desired point, rapidly reversing and returning it to the beginning of the cut at an increased speed, and



*Metropolitan-Vickers Electrical Co., Ltd.*

*Fig.* 199A. Double tyre-boring lathe with electrical equipment.

a rapid reversal for the next working stroke. It is desirable that the whole of the speed adjustment shall be carried out electrically to simplify the mechanical design of these massive machines. Time must also be economized by increasing the speed over idle intervals of the cutting stroke. Finally, the whole gear must be made so reliable that there is no possibility of overrunning, which would be attended with disastrous consequences to the machine as well as the work.

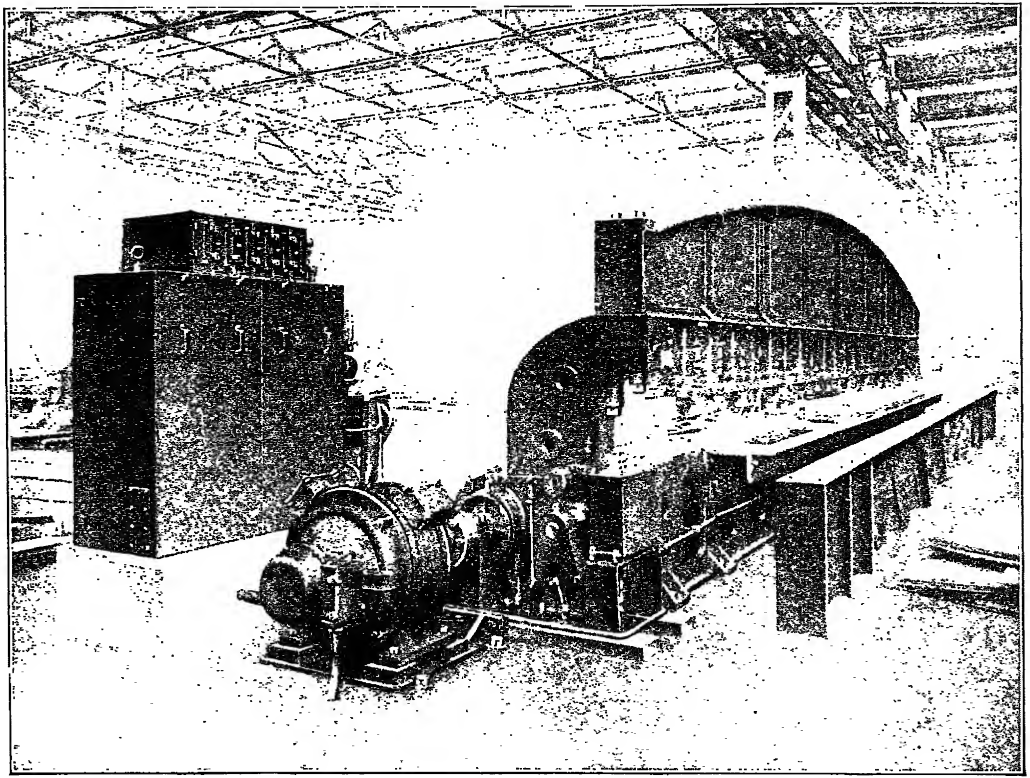
Now the method of control appropriate in any particular case depends upon the desired range of speeds, both for the cutting and the return strokes. If this can be covered by a 3 : 1 ratio or thereabouts a single D.C. machine may be employed as a driving motor, entirely controlled by means of contactor gear. But for A.C. equipments requiring the above range of adjustment, and for all cases requiring more than this and up to a ratio of about 10 : 1, a Ward-Leonard scheme is appropriate. It should, however, be noted that the latter more elaborate gear is not now considered as frequently necessary as used to be the case, at any rate with D.C. equipment.

Plate-edge planers are a specially simple class in which cutting is carried out in both directions, the load is constant, and there is no 'cutting air'. Automatic speed control is therefore not essential. Such a machine is shown in Fig. 200, driven by A.C., the three-phase solenoid brake being visible at the end of the machine. The master switch of these planers is usually operated by means of an endless cord extending the whole length of the bed, or by a spline shaft with lever on the tool head.

Small machines of the planer class may have the reciprocating motion produced from a unidirectional motor by means of a crank, cam, or belt-throwing arrangement. The control problem then becomes a simple one, and can be treated as for a boring-mill or lathe.

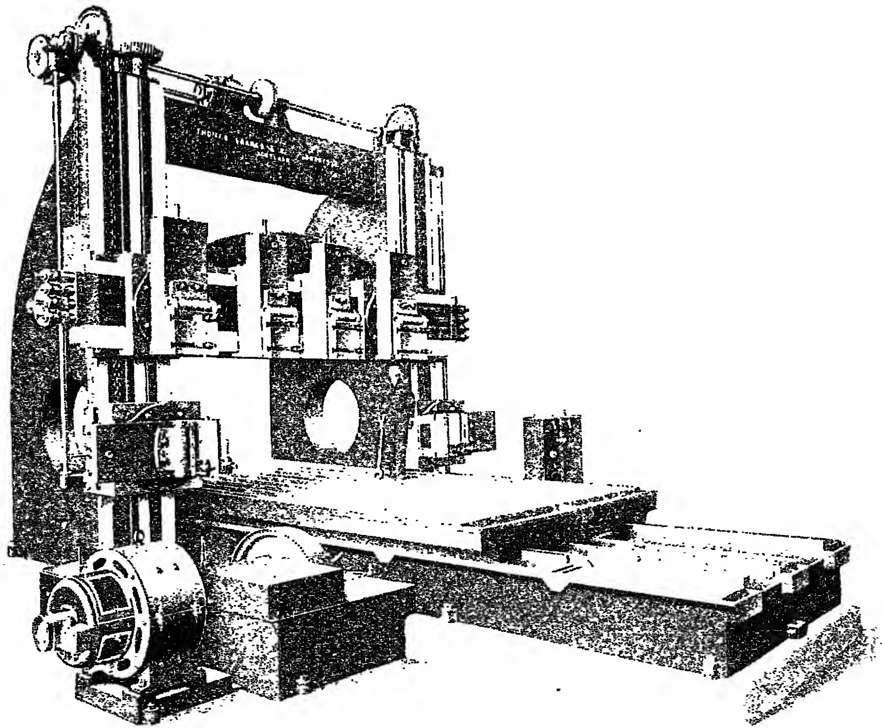
Dealing, however, with the typical larger machine in which the motor must reverse at the beginning and end of each stroke, it is evident that the task of bringing about quick acceleration and braking is the easier the less the inertia of the moving parts. This quantity is unfortunately augmented quite considerably by the motor itself, and it is hence necessary that the diameter of the armature or rotor shall be as small as possible. Planer motors are therefore made with rotating parts of greater length but smaller diameter than the ordinary pattern. Since the inertia effect is proportional to the square of the velocity, the use of a smaller motor rotating at higher speed is not a solution to the problem.

An effective D.C. equipment is shown in Fig. 201, the control gear for which is illustrated in detail in Fig. 202. The line contactors occupy the right-hand panel, and not only connect the motor to the line for forward and reverse running but apply a powerful dynamic brake by means of their lower contacts. There is only one step of acceleration, and this is effected upon the C.E.M.F. principle, one of the single-pole contactors being connected across the armature by an auxiliary contact on each line contactor as soon as the latter has closed.



*Metropolitan-Vickers Electrical Co., Ltd.*

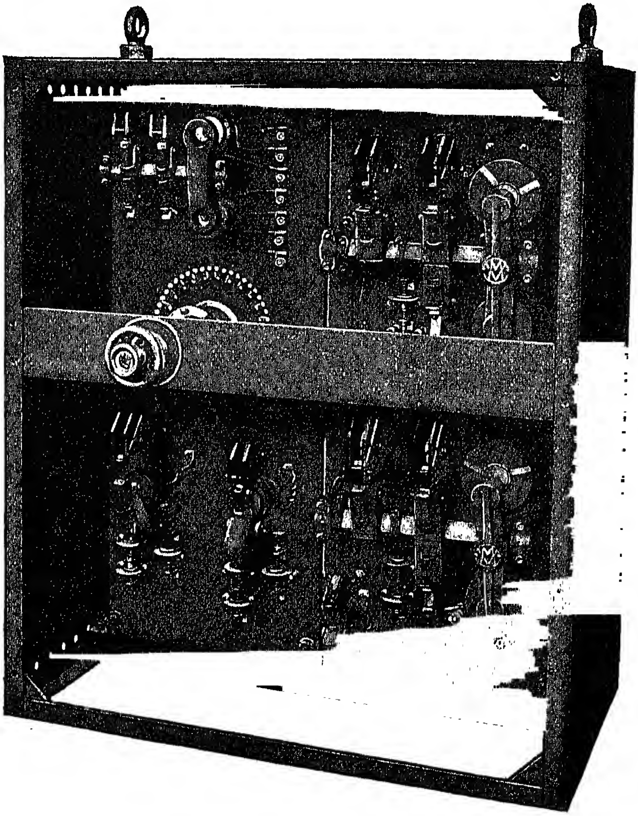
*Fig.* 200. Plate-edge planer, by Hugh Smith & Co., Ltd., Glasgow, driven by a 40 H.P. alternating current motor and controlled by push-button operated automatic contactor control.



*Metropolitan-Vickers Electrical Co., Ltd.*

*Fig.* 201. Heavy armour plate planer, by Thomas Shanks & Co., Johnstone, Scotland, driven by a

The excitation is maintained upon failure of the voltage by the inclusion of a special series winding on the motor (in addition to the usual 'stabilizing' compound winding) by means of the double-pole and double-throw contactor at the top of the left-hand panel, the object of



*Metropolitan-Vickers Electrical Co., Ltd.*

*Fig.* 202. Control gear for planer shown in Fig. 201, showing dynamic braking D.C. line-contactors and duplex speed adjustment.

which is to connect the coils in the correct direction for dynamic braking at each reversal of the line units. This requires four separate operating coils, two for closing in the first instance and two for holding closed, as the former are de-energized soon after the change in direction.

Speed control is effected by the two field rheostats arranged concentrically on the left, one being for the cutting and one for the return stroke. The same resistors are employed for both dials, and the change

is made from the higher resistance set by the 'return' rheostat to the lower value for cutting by connecting together the two moving contacts by means of another of the single-pole contactors, thus short-circuiting the added resistance. An auxiliary contact on the accelerating contactor holds this field contactor closed until it has itself closed, thereby preventing a start being made with the field unduly weakened.

The remaining single-pole contactor is for conferring inching and no-volt characteristics. A second electrical interlock is added to each of the line-contactors to prevent either from beginning to move until

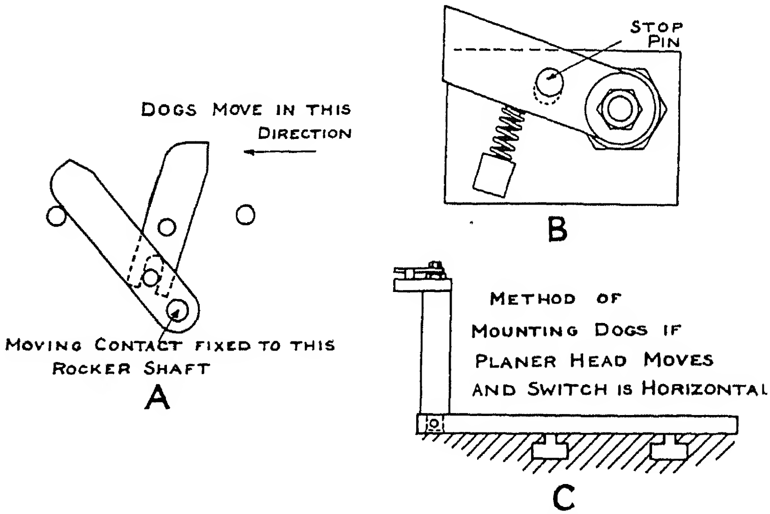
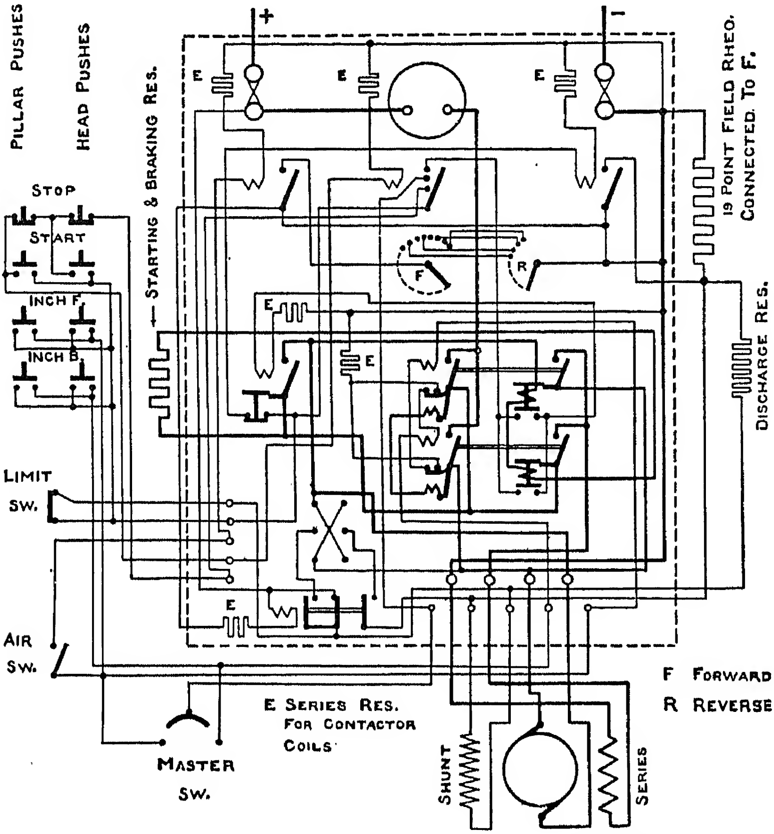



*Fig.* 203. Arrangement of air-cutting switch. A, side of switch, showing scissors operating lever. B, dog, showing spring for horizontal mounting. C, mounting for dog.

the other is fully opened. This is important as the dynamic brake does not come on until both pairs of lower contacts are touching.

Accelerating while 'cutting air' may be brought about by opening the 'field' contactor, thereby inserting the 'return' field resistance during a portion of the cutting stroke. An auxiliary switch and pair of spring dogs, whereby this contactor may be first opened and then closed as the machine continues to travel in the one direction, are shown in Fig. 203. The switch is of the drum pattern, as illustrated in Fig. 110, and is equipped with two levers, one of which is so pivotted to the case as to reverse the action of the other. If the planer is of the moving-bed pattern, like that in the figure, the dogs are clamped at the required positions in a T-slot running along one edge of the platen. Each is arranged to strike only the appropriate lever of the switch, one dog projecting more from the platen than the other; and as they are loosely pivoted, they ride over the levers without moving them during the

cutting stroke. For a machine of the fixed bed and moving tool-head pattern the switch is fixed to the head and the dogs are stationary. They may be fixed horizontally to vertical posts clamped to the floor or bed,

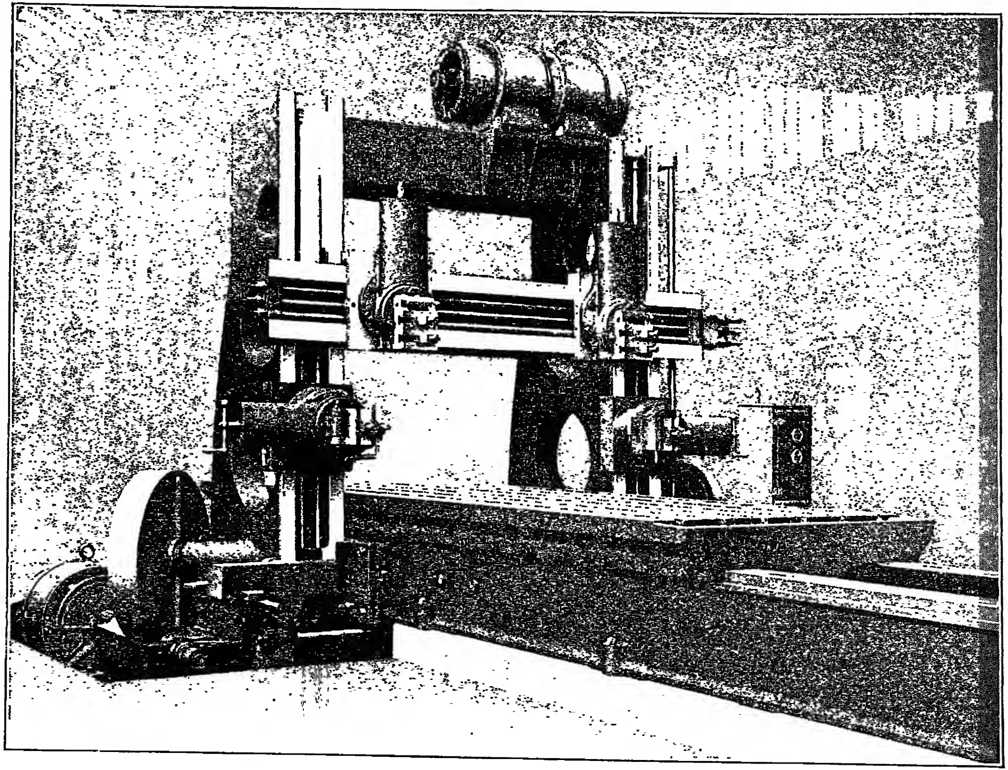



*General Electric Co., Ltd.*

*Fig.* 204. Connexion diagram for planer control.

and fitted with light springs to return them against the stops, as their weight is not now available to do this.

The limit switches open the coil circuits of the line contactors, and since an over-travel might possibly be due to the sticking of one of the latter, when the limit switch would produce no effect, it is a safe policy to provide a master contactor or circuit breaker which would also be opened by such a cause, or alternatively a limit switch carrying the line current might be employed.



*Metropolitan-Vickers Electrical Co., Ltd.*

*Fig.* 205. Armour plate planing machine, by J. Buckton & Co., Ltd., Leeds; driven by motor-generator set and 90 H.P. direct current motor with automatic push-button operated contactor control.

The connexion diagram in Fig. 204 shows a scheme having the following points of difference as compared with that just given :

(1) There is an additional field contactor for entirely short-circuiting the field resistance during braking and acceleration.

(2) Excitation is maintained upon failure of voltage by connexion of the existing shunt field to the brushes, the correct polarity being secured by a mechanical relay operated by the line-contactors upon closing, this relay being connected when it is required to function electrically by a no-volt change-over relay, as shown in Fig. 120.

(3) The control resistance is so located that it functions also for dynamic braking.

(4) Current-limit acceleration is employed.

The diagram also shows the connexions to the main fuses and ammeter. All panel components are in the actual positions occupied in the apparatus.

¶ WARD-LEONARD CONTROL.—When motor-generator control is used, somewhat similar functions to the above are carried out in the exciting instead of the main circuit. Instead of the potentiometer regulator shown in Fig. 143, a duplex rheostat is employed as with the above scheme. A convenient arrangement is for one variable resistance to be connected in the generator field to give, say, a 1 : 5 speed reduction for adjusting the cutting speed, and the other in that of the motor, giving a 2 : 1 increase for varying the return speed. These are alternately cut in and out by two small contactors, or even auxiliary switches mechanically operated by the platen, at the same time as the generator field is reversed by a similar means.

Since the motor of the motor-generator set runs at constant speed and is not controlled in any way after it is once started, the scheme is equally suitable for D.C. and A.C. supply circuits. A typical planer of this type is shown in Fig. 205, the motor-generator being mounted upon the cross-beam of the machine structure. The illustration also shows the standard method of applying the driving motor by means of worm gearing.

¶ POWER DEMAND.—The sizes of motor in horse-power required for driving typical machine tools are given in Tables 15, 16, and 18 in the Appendix.

## XXII

## THE CONTROL OF CALENDERS AND PRINTING PRESSES

THE word 'Calender' is a corruption of 'cylinder', and signifies a machine in which a material is passed between cylinders or rollers. Such a process is used in the manufacture of paper, rubber, and cloth, and the modern high-speed rotary printing press is a similar machine, in which the type are actually cast in cylindrical form and the paper passed continuously over them. A characteristic of all these processes is that they must be initiated by a preparatory rotation at a very low speed, such as 5 per cent. of the maximum, during which the material is introduced and engaged with the means that is to bring about its full-speed passage as soon as the normal process has begun. The provision of the two extremes of speed, namely, the initial creep and the full working speed, constitutes a problem common to this type of machinery. Flat-bed printing presses work under somewhat different conditions, but for the sake of completeness they will also be dealt with in this chapter.

It is true that the use of resistance in series with the armature of a shunt motor, and also a diverting resistance in parallel with it, will give very slow running; but unfortunately the voltage drop in these varies with every change of load, and therefore the speed becomes unstable when it is reduced in this manner by more than about 75 per cent. When in addition it is required that a very gradual start shall be made from rest, the above methods are often quite inadequate; for the considerable static friction requires an amount of resistance to be cut out which will cause a rapid increase of speed as soon as motion begins and the friction reduces to the running value.

Ward-Leonard control has been used in the past for rotary printing presses; but, as has been pointed out in connexion with mine hoists, the use of three machines in place of one is only justified when there are frequent periods of acceleration and retardation. In most of the present cases this is not so, steady running conditions obtaining after the preparatory period has come to an end. An example of this type of control derived from the rubber industry is given later.

Each type of calender has its own peculiar requirements, and these will be dealt with in detail later; but it is first proposed to enumerate the various general methods available for machinery demanding a low preparatory speed, apart from the ordinary 'inching' starter already described on p. 49, which is only suited for the smaller and less exacting equipments.

First, for fairly small D.C. motors requiring a comparatively narrow speed range, such as about 1 : 8, a motor with a 3 : 1 or 4 : 1 range provided by field adjustment can be employed, and the creeping speeds

for preparation obtained by series and diverting resistances. A number of economical working speeds are afforded by the field regulation after the preliminary resistances have been cut out.

Secondly, the above scheme may be employed with the addition of double-voltage control. It was mentioned in Chap. VI that advantage is rarely taken of the existence of the two voltages in the third-wire system for speed regulation purposes, and the present is the most notable instance in which use is made of this facility. The method may be utilized to extend the speed range, or it may enable a motor with a 2 : 1 adjustment to be substituted for a 4 : 1 model. The latter is bigger and hence more expensive than the former ; for whereas with voltage control the field is of constant strength, and the armature current therefore constant for a given torque, in the case of field control the armature current varies inversely with the field strength under the same conditions. The result is that the armature in the latter case must be designed to carry the heavy current obtaining when the field is weakest, and the size of the whole machine is increased thereby.

The application of the two-voltage system is indicated in the diagram forming Fig. 206, in which the armature circuit only is shown. Three classes of resistance are included in the scheme, namely, those for diverting, for accelerating, and for the transition from low to high voltage and vice versa. Of these, the last is the only one that has not been used in previous schemes ; it is added to enable the change-over to take place without the circuit being opened. Since there is usually a considerable amount of friction in the load upon a calender, especially one dealing with rubber, an open circuit even of short duration would cause a serious falling-off in speed, and must therefore be avoided.

Eight contactors are employed in the diagram for governing the speed, including Nos. 1, 7, and 8, which lead to the negative, neutral, and positive mains respectively. They are operated as follows :

| | |
|---|---|
| Thread-in speed . . | Close 1, 2, and 7. |
| Slow speed . . . | Open 2. |
| Acceleration to half-speed | Close 3, 4, and 5 in succession. |
| Transition to full voltage | Close 8, then open 3, 4, 5, and 7. |
| Acceleration to full speed | Close 6, 3, 4, and 5 in succession. |
| Stop . . . . | Open 1 and 8, and close 2. |

The accompanying adjustment of the field circuit need not be described.

Thirdly, the Holmes-Clatworthy two-motor system is available for obtaining extreme variations in speed together with complete stability. This was first used, in 1898, for the driving of rotary printing presses, and involved the use of a small auxiliary motor, coupled to the main motor-shaft through the medium of a self-releasing clutch and a reducing gear. Threading-in is effected at a speed of about 5 revs. per min. by means of the smaller motor alone. When the preparatory stage is completed, the main motor is brought into action and takes up the drive without shock ; and at the same time the auxiliary motor is

automatically disconnected both electrically and mechanically. This motor is also similarly disconnected when the installation is at rest, and thus does not interfere with the barring of the machine.

Two modifications of the above scheme are in existence. In the first the main motor is connected in circuit together with the auxiliary unit, but the series resistance employed with the former is made slightly larger than is appropriate for the desired speed. The smaller motor, being shunt wound and having little or no resistance in series with its armature or rotor, maintains the speed constant, supplying sufficient power to accomplish this end. Since it only takes part of the load it may be made smaller than in the previous case, where it was compelled to do the whole of the work at feeding-in speed.

For the second modification the armature of the small motor is connected in series with that of the larger one; a proceeding which not

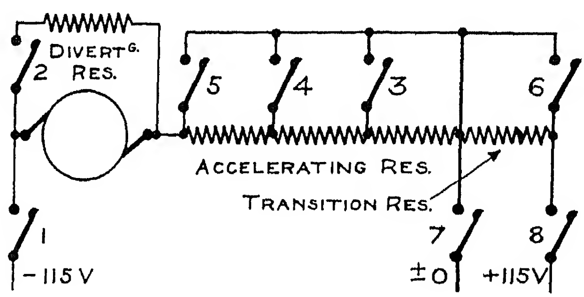



*Fig.* 206. Diagram of double-voltage control scheme for obtaining a wide speed range.

only absorbs a considerable amount of the total voltage in the form of back E.M.F., but varies this absorption in proportion to any change of speed. The latter is thus effectively stabilized, as the effect of a change in this respect is to reduce the voltage applied to the larger armature.

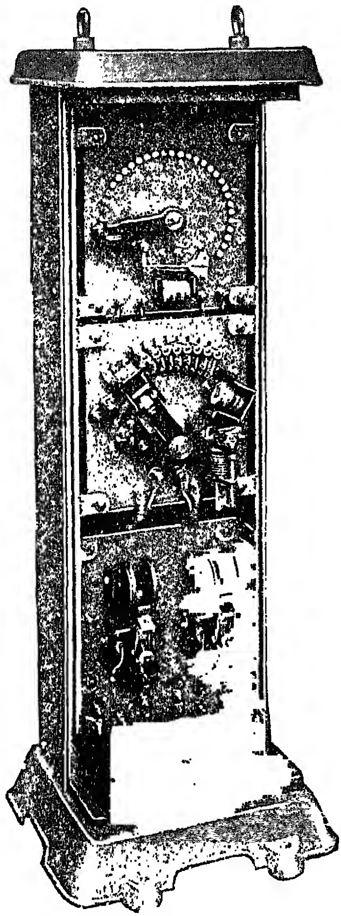
Of the three two-motor variants the third can only be used with D.C. motors, but the two former are applicable to A.C. working. With A.C. equipments, however, the only means of speed adjustment is by series resistance in the rotor circuit, and there is thus only one economical running speed. A solenoid brake, also, must be used in place of the more convenient dynamic type.

A fourth and final method consists in the interposition of a change-speed gear, such as the Williams-Janney, between the motor and the load, just as is described in connexion with mine hoists on p. 270.

General requirements for calender control are, first, the operation must be convenient and suitable for unskilled operation. A particularly appropriate method is by means of push-buttons, every change being brought about by the pressing of one out of four or five of these switches. Secondly, it must be possible to stop, and it is in many cases

preferable also to start, the motion from a number of stations round the driven machine. Thirdly, it must be possible in most cases to 'inch' or 'jog' the machine when setting up, preferably by means of a special button.

Details of the methods of control that have been described above, together with requirements peculiar to the various types of calender, will be given in the following sections.



*Igranic Electric Co., Ltd.*

*Fig.* 207. 'Varispede' panel with front cover removed for controlling rubber calenders and similar loads.

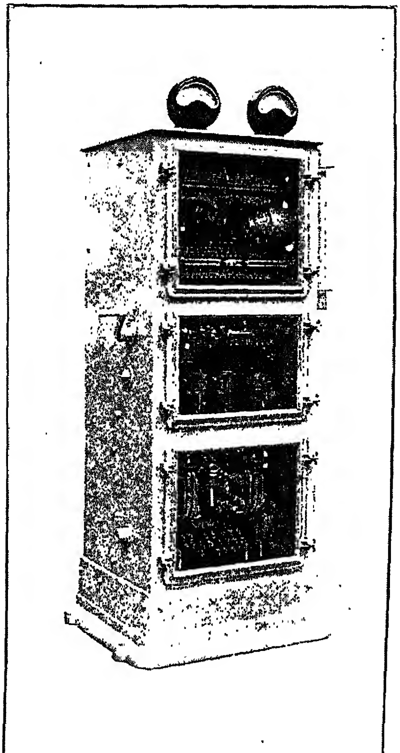
¶ Rubber Calenders.—Practically the whole process of manufacturing rubber goods, comprising cracking, mixing, and calendering, consists of passing the material or materials between steel rollers. The first two operations merely call for constant speed and ordinary manual starters, preferably of the drum type; but the last requires the specialized control with which this chapter is concerned. The need for a low preparatory speed is well exemplified, for the danger to the operator is a real one if this be too high.

Two types of material require feeding-in, namely the raw rubber and the fabric, of which the former introduces little danger, since the sticky mass adheres to the surface of the rollers and is drawn in without much assistance from the fingers. At a certain stage it is, however, necessary to enter the end of a roll of cloth, and with this there is serious danger of the workman's nails, or even his whole fingers, being caught between the rolls. The importance of a fairly wide range of speed, and of close regulation, will therefore be obvious. It is not usual, however, for a diverter resistance to be employed, most manufacturers being satisfied with field and armature resistance control only.

It is desirable, but not essential, that the motor be reversed, largely for cases of emergency. In the most complete equipments this is provided by means of reversing line-contactors, complete with 'reverse' push-button, holding contacts, and reverse interlock; such an installation is especially desirable when the control panel is remote from the

machine. In other cases the armature is connected to its circuit through a hand-operated reversing switch.

The single-motor type of control is at present that most used for rubber manufacture, and will therefore be described in this connexion. Although the power is usually purchased in the form of A.C., so much advantage as regards speed control is to be gained by conversion to D.C. that this is generally done for supplying the calenders. Unless the two-motor arrangement is adopted, A.C. operation necessitates such complications as a slipping clutch, pole-changing, or multiple frequency, and these are apt to be inconvenient and expensive.



*Brookhirst Switchgear Co., Ltd.*

*Fig.* 207A. Control pillar for rubber calenders, Ward-Leonard system.

The pillar shown in Fig. 207 is a form frequently employed for controlling rubber calenders of small or moderate size, giving robust starting capabilities and a wide range of speed control by field regulation. Inching is effected by a momentary movement of the main arm, which is provided with an 'inching' attachment or 'arc-preventing interlock' resembling that described in Chap. IV. There are also auxiliary arcing contacts above the contact studs. Starting on a weak field is guarded against by providing a no-volt release device in connexion with the regulator arm.

Larger and more elaborate schemes would be controlled by contactor gear, and would possess some or all of the following additional features :

Reversing contactors.

Dynamic braking.

A set of five main push-buttons, marked 'Forward', 'Reverse', 'Stop', 'Slow', 'Fast'.

A number of duplex safety push-buttons, marked 'Lock' and 'Free', or 'Safe Stop' and 'Run'.

A field accelerating relay.

Of these, the safety pushes are of importance for this class of drive,

as they prevent the machine from being started from any other station when the 'Lock' or 'Safe' push has been depressed. Unlike the other push switches employed, they together operate a single pair of contacts, interrupting the main exciting circuit for the contactors, and remain in the on or off position in which they are left. An operator can therefore work at any part of the machine with the assurance that it cannot be started unless the actual switch he has pressed is restored to the open position.

The most complete control is of course given by the Ward-Leonard system, an example of which is afforded by the control pillar in Fig. 207A. This unit has been designed to work in conjunction with a motor, supplied by a motor-generator set, the speed of the former being varied from 60 to 600 revs. per min. by the field regulation of the generator, and from 600 to 950 by regulation of the driving motor. The most interesting item in the figure is the motor-operated potentiometer regulator on the top panel, by means of which the same resistance units are cut into and out of both fields, the speed adjustment being continuous over the whole range. There are 201 contacts in this regulator, and the servo-motor has a three-point rheostat in its armature circuit which permits the complete travel to be accomplished in 20, 30, or 45 seconds respectively.

The equipment is operated by means of five push-buttons, labelled respectively 'Start', 'Stop', 'Emergency Stop', 'Increase Speed', and 'Reduce Speed'; and most of the remaining components of the pillar are associated directly with these. Behind the middle door, for example, may be seen the two relays for connecting in the servo-motor for forward or reverse running, while the main contactors are at the bottom. The handle on the left operates a special change-over switch for energizing the control circuits from one of two alternative supplies. To the right of this last is the exciter field regulator.

¶ PAPER CALENDERS.—The machines employed for the manufacture of paper have a requirement peculiar to themselves, in that the relative speeds of the various sections must always be exactly constant. A paper calender consists of a very large number of rolls which are usually divided into sections, and for electrical drive it is the most convenient arrangement to drive each section by a separate motor. The paper pulp is passed round all these rolls in turn, beginning at one end as an even thickness of wet fibres spread upon a wire support, and ending at the other in the form of the finished product emerging from the drying rolls. It will be evident that any unpremeditated difference in speed between the various units or sections will cause doubling or rupture of the paper and consequent loss. The problem is complicated by the shrinkage of the paper during the process, which must be allowed for by accurate speed adjustment of the different sections.

It was the practice before the days of electric drive to use cumbersome mechanisms with thick and heavy belts in order to keep the speed sufficiently uniform, and this entailed great expense in first cost and

in upkeep. The principal difficulty in connexion with the use of electr motors is that whereas they may be minutely regulated to give a requir speed at any instant, the latter will not necessarily remain consta thereafter. Consequently the various early attempts to drive such mill electrically were failures. It will therefore be seen that a meth is required which will enable the motors to be regulated in such a w that their speeds will maintain the same relationships with one anothe and this is provided in a typically simple manner by means of the Ha land Interlock system, which will serve as an illustration.

It is the practice to drive the section motors by means of a motc

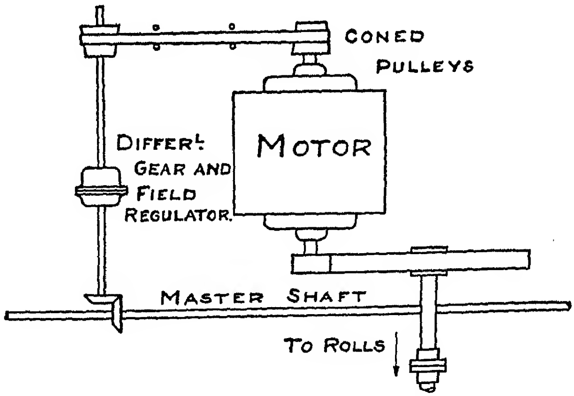



*Fig.* 208. Harland ' Interlock ' system of co-ordinating speeds of motors for paper-making machine.

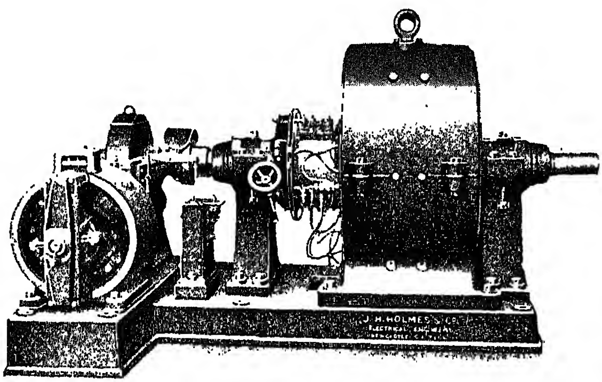
generator set, equipped with an exciter, the latter serving not only : the generator fields, but for those of the motors as well. Adjustm of the speed of the whole machine is effected either by regulation of t generator voltage, or for the production of papers requiring a higl finish by the combined regulation of the generator and motor fields.

The Interlock system depends upon the principle of the well-kno differential gear as applied to the drive of a motor-car. If the t horizontal shafts are rotated at exactly the same speed in oppos directions, the frame supporting the two connecting pinions will 1 move. If, however, one of the shafts runs faster or slower than 1 other, the frame rotates in one or the other direction. In the interlc scheme one of the horizontal shafts sets the standard speed, and frame is connected to the moving contact of a field regulator hav about 100 steps, and adjusts the speed of the motor concerned.

This arrangement will be seen in Fig. 208, in which the motoı shown driving the machine by means of spur gearing. The sn master shaft running transversely to the motor spindles fixes the spe and is usually driven by the motor of the drier section. One of spindles of the differential gear is connected by bevel gearing to t

master shaft, while the other is belted by means of slightly coned pulleys to the other end of the motor shaft. There is a provision whereby the position of the belt can be adjusted on these pulleys, in order to obtain small adjustments of speed to compensate for the 'draw' of the paper.

In the apparatus shown the field regulator is contained in the same case as the differential gear. It has been found that this arrangement works quite successfully, the speed of the motor being kept at exactly the right point. Usually the appropriate speed lies between those corresponding to two adjacent regulator studs, and the contact




*J. H. Holmes & Co.*

*Fig.* 209. Holmes-Clatworthy motor equipment for driving rotary presses.

slowly fluctuates from one to the other, somewhat after the manner of a Tirrill regulator or field accelerating relay.

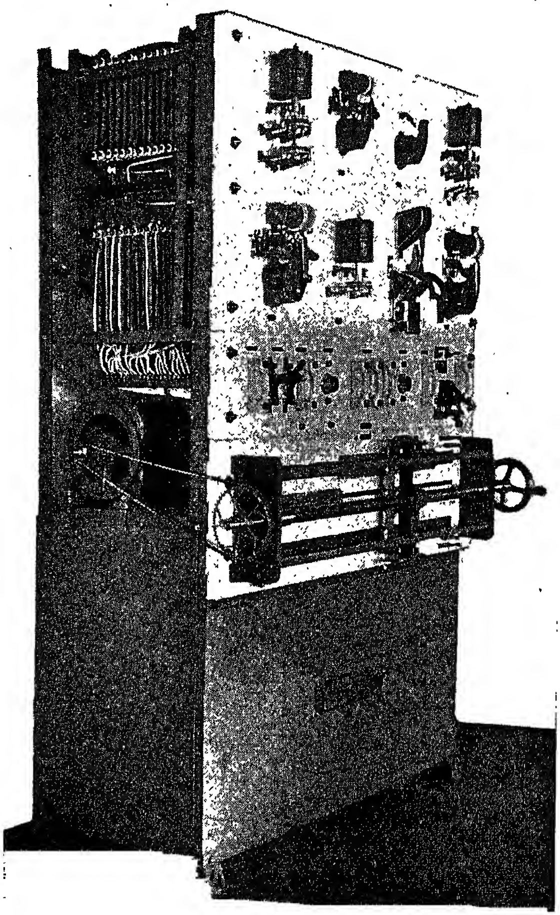
The starting of the section motors is carried out very much as with printing presses and calenders generally, a row of contactor panels being provided for the various units. Slow creeping speeds are necessary when new Fourdrinier wires or felts are being put on, and it is also necessary to provide for inching for purposes of inspection.

A synchronous motor system of co-ordination for paper-making machines was briefly described on p. 21.

¶ Rotary Printing Presses.—The requirements with regard to the driving of a rotary printing press are particularly severe, and it is a matter of urgent necessity that the smoothest and most reliable speed control should be effected. The arrangement in Fig. 209 shows the two motors of the Holmes-Clatworthy system as they are arranged for this species of drive, the small motor being connected by worm gearing to one end of the shaft of the large motor, with a magnetically operated clutch interposed between the two.

The motors are controlled by the equipment shown in Fig. 210, the

most important component of which is the motor-operated distributing switch at the bottom of the panel. The control gear is operated by



*J. H. Holmes & Co.*

*Fig.* 210. Full-automatic control gear for Holmes-Clatworthy system.

means of the set of push-buttons shown in Fig. 211, any number of which may be employed at various parts of the machine, in addition to further 'Stop' buttons if desired.

On pressing the 'Up' button the pilot motor begins rotating, and starts up the small motor by means of the contacts at the left-hand end of the series. As soon as full speed for this machine has been reached,

the large accelerating contacts for the main motor are connected, while the small unit is cut off, and mechanically disconnected by means of the clutch. Acceleration now proceeds on the large motor in the usual manner. The process can be reversed by pressing the 'Down' button.

¶ FLAT-BED PRESSES.—The arrangement of a flat-bed press is not unlike that of a planing machine, in that the bed is reciprocated to and fro, with the type or lithographic stone clamped upon it, passing under the inking roll at one end and the 'impression' roll at the other. As with a small planer, a D.C. compound or A.C. slip-ring motor is employed to negotiate the very fluctuating load; but the reciprocation is provided for by the mechanism of the press, and consequently the motor rotates continuously in the one direction.


*Fig.* 211. Push-button set for operating Holmes-Clatworthy automatic printing press controller

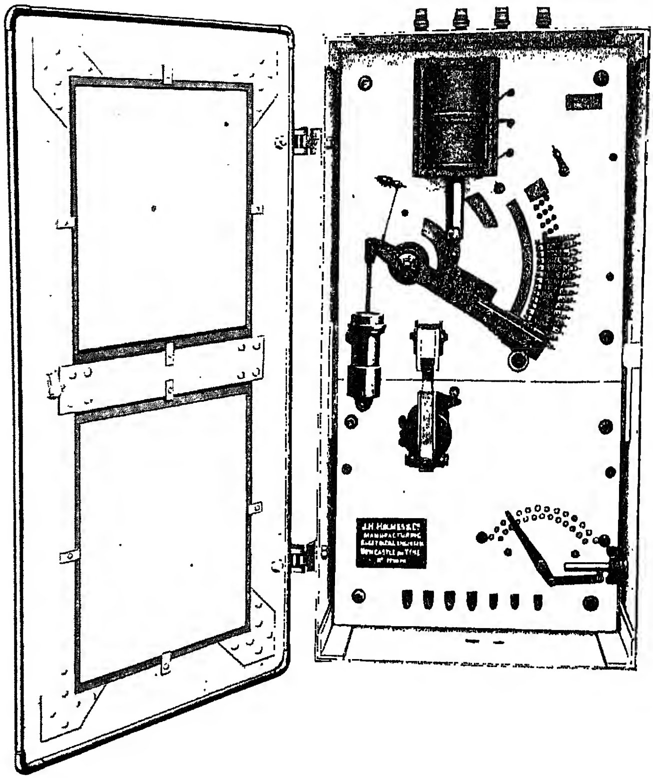
Manual or time-element face-plate starters are appropriate for this work. For the larger presses push-button operation is the rule; but in general the control gear is of a simple description. Speed adjustment is usually provided by field and armature resistance in the case of D.C. plants, and rotor series resistance for A.C. motors. The more elaborate schemes, also, would include inching characteristics, dynamic (or solenoid) brake, and perhaps reversing for emergency purposes.

A suitable form of control gear for the larger units is the time-element face-plate starting pillar shown in Fig. 212. This is operated by push-buttons conveniently situated on and near the machine. By pressing the 'Start' button the contactor is closed, and the solenoid gradually cuts out the armature series resistance, and then begins to accelerate the motor by cutting resistance into the shunt field. The smaller field contacts at the upper part of the movement are, however, connected in parallel with the manual rheostat at the bottom of the case, possessing twice as many contacts as there are above. This rheostat short-circuits any desired proportion of the total regulating resistance, thus limiting the increase of speed to the predetermined figure.

An inching button closes the contactor, rotating the motor momentarily with all resistance in, without operating the solenoid. It is of course impossible with this gear to attempt to start upon a weak field.

¶ VARIABLE SPEED GEARS.—Instead of employing resistance control a mechanical variable speed gear may be interposed between a constant speed motor and the load. This case does not in reality come within the scope of electric control at all, for the motor is now a plain shunt or squirrel-cage model with the simplest of starters. A description will, however, be given of a typical variable gear, as such a one may be of service under certain circumstances.

The section forming Fig. 213 illustrates the principle of the Williams-Janney oil-pressure gear, which has already been mentioned in connexion with mine hoists. It is of interest to electrical engineers in that it is a hydraulic reproduction of the Ward-Leonard principle, there being two units in the figure corresponding to the generator and driving

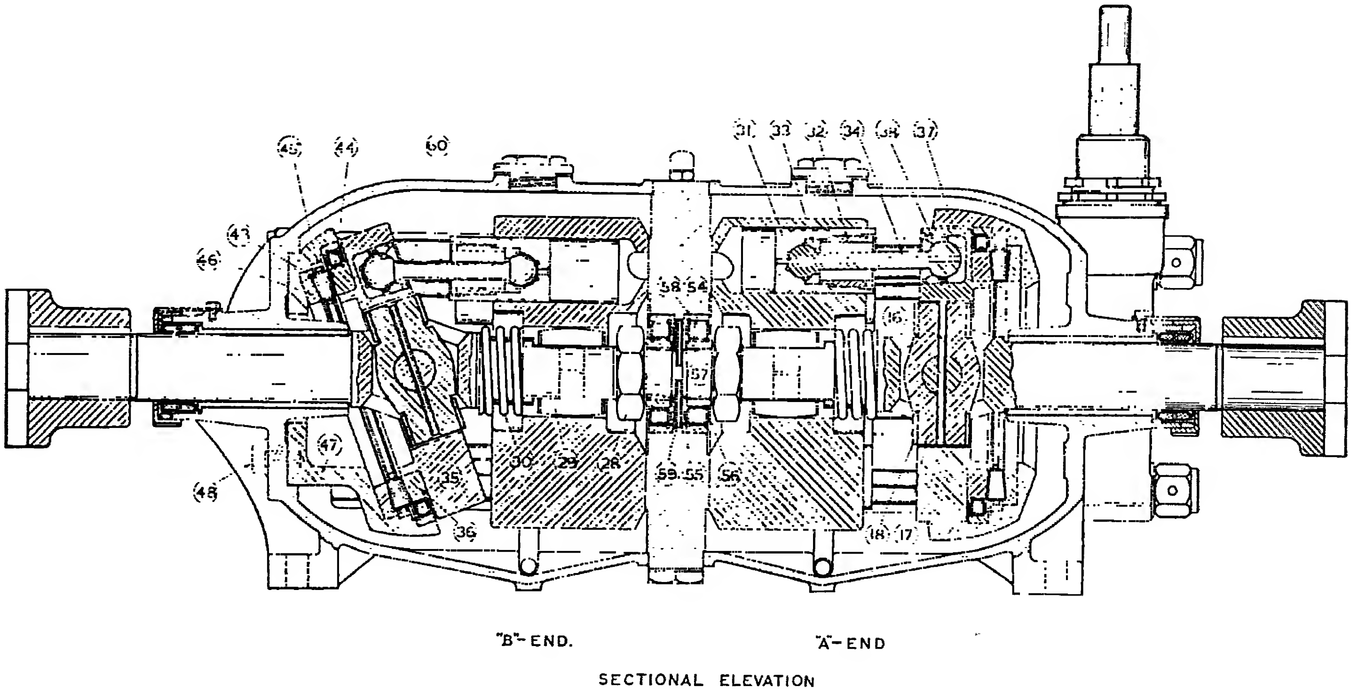


*J. H. Holmes & Co.*

*Fig.* 212. Automatic solenoid controller for flat-bed printing presses and similar drives.

motor of the electrical apparatus. These two units may be combined, as shown, or they may be separate and joined by a pair of pipes, as illustrated in Fig. 214, representing the driving of a fabric printing machine.

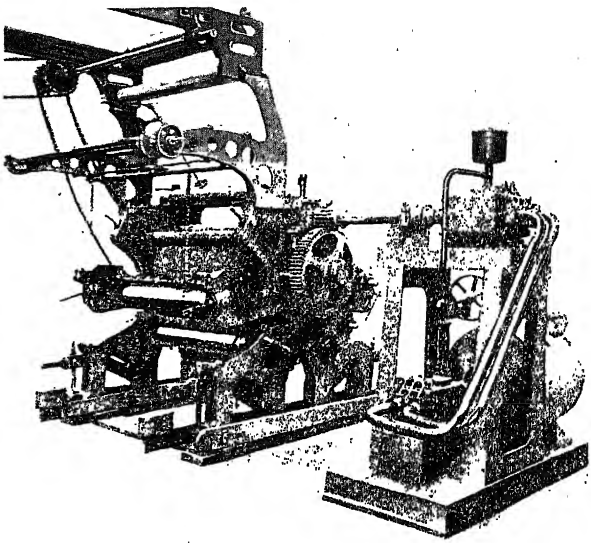
Both units are alike, each consisting of nine small cylinders connected to the shaft through the medium of an oblique disk which takes the place of a crank; the plentiful use of roller bearings doing away with the friction that would otherwise render this simple method very wasteful, and enabling an overall efficiency of over 80 per cent. to be




*Variable Speed Gear Ltd.*

*Fig.* 213. Section of Williams-Janney variable speed gear, showing pump element on right and motor element on left.

attained. The inclination of the motor disk, shown on the left in the figure, is fixed, giving the cylinders a fixed stroke ; but that of the pump on the right is variable on both sides of the neutral position at which it is shown in the figure and which brings about standstill, so that any



*Variable Speed Gear, Ltd.*

*Fig.* 214. Fabric printing machine with motor and speed gear.

fraction of the maximum speed in both forward and reverse directions may be obtained from the motor element by the simple adjustment of this inclination by means of a single operating shaft and worm gear.

The outstanding advantage of such a piece of equipment is its smooth regulation of the speed, and the inclusion of a reversing capability without additional complication. The example in Fig. 214 shows the convenience to be derived from separating the two elements.

¶ Power Demand.—The sizes of motor in horse-power required for driving printing machinery are given in Table 19; and for calico printing, bleaching, and finishing in Table 20, in the Appendix.

## XXIII

## MISCELLANEOUS CONTROL PROBLEMS

THE examples of electric operation and control that are dealt with in the foregoing chapters have been so chosen as to represent the employment of electricity in large industries in which conditions are of such an exceptional nature that special means have to be adopted to achieve success. Most other cases can be catered for by the application of the general principles given in the earlier part of the book. There are, however, a number of isolated instances that do not fall within any of the broad categories that have received detailed treatment, but which merit brief notice. A few of the more notable of these will be included in this chapter.

¶ LARGE VALVES.—The flow of steam, water, and other fluids is controlled by valves, the operation of which becomes extremely laborious as soon as the diameter exceeds a few inches, especially when water at pressures exceeding 100 lb. per sq. in. is being dealt with. For apertures of approaching 2 ft. the amount of time occupied in opening or closing them by manual labour becomes a serious matter, especially in those situations where a quick action is needed. Many valves, again, are preferably located where it is inconvenient, dangerous, or even impossible for an operator to make his way. The services of the electric motor overcome both these difficulties, and are frequently employed.

To secure the most compact and robust design the motor should be attached directly to the valve casing itself, and connected to the operating spindle by strong but simple gearing. The most suitable type of motor can be deduced from the load to be overcome during the cycle of closing and opening. When starting from the full-open position the load is light, increasing considerably, however, as the aperture is narrowed and closed. But the greatest effort is required at the beginning of the opening operation, especially if excessive force has been previously employed in closing, or if the valve has been left closed for a long period. Since the greatest torque occurs at starting, therefore, a D.C. series motor is the best form to adopt. In addition to affording the strong initial effort that is essential, it is able to speed up when the torque is less and thus economize in time. For A.C. circuits the squirrel-cage machine with high resistance rotor, designed for maximum torque at starting, is satisfactory, but, as in other applications, will require to have a somewhat higher rating than the D.C. motor, probably to the extent of about 33 per cent. Totally enclosed frames only should be used.

There are two mechanical expedients by which the work of the motor is frequently made more effective. The first of these is a loose coupling in the gear train, whereby a certain amount of ‘ lost motion ’

occurs before force is actually applied to the valve. By this means the motor is able to store up energy that is suddenly concentrated in moving the valve from its seating, a procedure that is specially useful with the A.C. motor. The second device is a mechanical coupling that is able to slip in the closing direction when a given pressure has been exceeded, and thus avoid jamming the valve. There must be no slip, however, when opening is taking place.

The control gear appropriate for valve operation may be classed under three headings, namely, manual, automatic, and self-regulating. Of these the first would consist of a simple drum controller, the second of a small contactor equipment with push-button or other simple manipulation, and the third of a torque-motor arrangement. The most usual

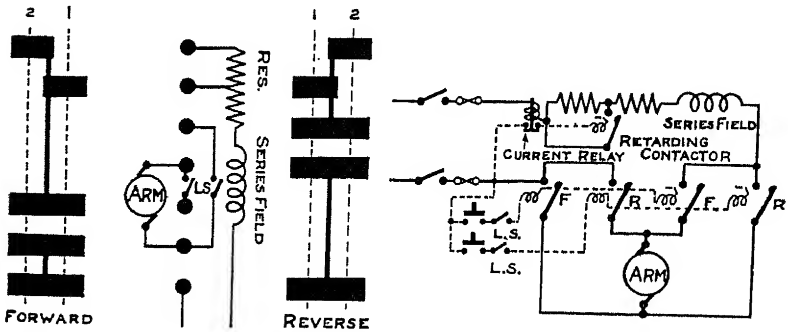



*Fig.* 215. Scheme for the operation of large steam or water valves by series motors: A, by drum controller; B, by contactor gear.

cases will be described, namely, the use of D.C. for the first two and A.C. for the third, leaving the very similar designs for the other systems to be worked out by the reader. Limit switches for both extremities of the travel, and visible indicators as to the position of the valve, are valuable safeguards against fracture of the operating spindle or other part, and these should be included.

Since the motor will not greatly exceed 8 H.P. for the largest valves, unless the period of operation is to be shorter than about a minute, even the D.C. motor can be switched directly on to the line, with merely a small resistance connected permanently in series with it for the larger sizes. A further resistance should, however, be inserted after the heavy initial torque of opening has been overcome, to prevent the motor racing and perhaps overrunning the end of its travel.

Corresponding drum and push-button control schemes are shown in Fig. 215, in both of which permanent and slowing resistances and also limit switches are employed. The manual controller needs no comment. The automatic equipment is a simple arrangement of five small contactors, four being reversing line units and one a retarding contactor which cuts in the additional resistance when the current relay drops,

indicating that the load has fallen below a certain predetermined point. As shown, the push-buttons, if of the 'spring-off' type, would require holding down while the operation was in progress; but the addition of holding contacts to two of the line-contactors, as in Fig. 102, would enable them to be let go immediately, leaving the limit switches to stop the motor. A dynamic brake is scarcely required, especially as the final closing of the valve would have to be accomplished after the limit switch had opened and thus while the motor was drifting. If needed in a particular case its addition would not be difficult.

An automatic regulating valve is required in such processes as paper-making, where the water pressure must be regulated to prevent fluctuations in the current demand of the driving motor. In this case the valve, which does not have to work against any great pressure, is adjusted by a squirrel-cage torque motor geared to it, with series wound stator windings fed from current transformers in the leads of the pulping or other supplying machinery. The motor operates against a controlling force consisting of a spring or counter-weight suspended from a pulley on its shaft, just as in the case of the torque relay described and illustrated on p. 165.

¶ ELECTRIC PUMPS AND COMPRESSORS.—The pumping of water by electricity possesses two outstanding advantages, namely, that it is very readily made automatic, and it usually forms a valuable off-peak load, which can hence be supplied at specially low rates. In general, the control of pumping plants, both of the centrifugal and piston type, is carried out along the broad lines discussed earlier in the book; but a few additional notes may be appended.

Either type of pump is driven to the best advantage by means of a compound motor upon D.C. systems, or an induction machine upon A.C. Small installations of $\frac{1}{2}$ H.P. with D.C. or up to 5 H.P. with A.C. may be simply switched on and off by means of a float or diaphragm switch such as those described on p. 159. Above those sizes, star-delta or resistance starting is employed in conjunction with contactors in the usual manner. Squirrel-cage motors can be employed, when the supply authorities permit, up to about 150 H.P., especially those with a double-deck winding capable of being switched straight on to the mains. Almost the only case which requires special caution is that in which a long water column has to be accelerated with a piston pump, calling for correspondingly gradual starting.

The most notable purpose for which electric fans are used on a large scale is the ventilation of mines. Frequent starting is not a requirement here, in fact the best modern practice is in the direction of keeping the plant running at constant speed day and night, week-ends and holidays. At one time it was standard practice to reduce speed during off hours; but it is now more generally considered desirable to maintain the full ventilation continuously. Moreover, by employing a synchronous-induction motor, which of course demands constant speed, a most valuable economy may be effected in the mine installation as a whole

through the medium of power-factor correction. This form of motor is in addition a comparatively cheap one, and runs at a high efficiency.

It should be noted that a considerable torque must be developed at about the maximum load, for pulling the rotor into synchronism, and that the ordinary self-starting synchronous motor is not suitable for such duty unless a friction clutch is fitted for starting purposes. A progressive increase of capacity in the fan, as required by the gradual development of the mine itself, is best provided for by changing the gearing between motor and fan.

Air compressors also are employed to a great extent in mining practice, although requirements are very much the same in other fields. Self-starting synchronous motors are applicable, together with the tap-starting scheme shown on p. 89. Starting conditions are fairly exacting, and while this method is quite satisfactory, trouble may occur if a simpler auto-transformer method be adopted. It is customary to run large compressors continuously, and relieve surplus pressure in the reservoir by means of an unloading valve.

¶ Swing and Lift Bridges.—The operation of swing, lift, and bascule bridges presents a number of distinctive features that deserve a brief reference. Of these the most important are due to the great weight of the moving parts, and the magnitude of the disaster that would occur if there were any material deviation from the predetermined cycle. If, for example, a lifting motor began its rotation in the wrong direction, or failed to stop at the end of its appointed travel, or even exceeded its proper speed at the instant of closing, a very costly and vital structure would be liable to extensive damage, involving great financial loss and risk to human life. This must obviously be avoided by every possible means, and in addition the requisite degree of reliability must be secured not only when the equipment is clearly visible to the operator, but also during the hours of darkness.

Safe operation is obtained chiefly by simplicity of design, coupled with the use of a well-chosen system of interlocks, signals, and brakes. Fully automatic control gear is not an essential, as high speed is deliberately sacrificed to safety. Thus manual gear is met with as well as that employing self-acting acceleration. The great requirements are that the motions shall always be carried out without any suspicion of shock or jar; and that a second line of defence shall always be provided against the failure of any component.

Motors are installed to fulfil three functions, viz. to perform the main operation of swinging or lifting, to lock the span in its open or closed position, and to operate the gates; the lock motors commonly travelling with the span, and needing only a 15-minute rating. Series or slip-ring induction motors are typically employed; but for locking, which requires only about 5 H.P., a squirrel-cage machine with high-resistance rotor is appropriate for A.C. equipments. The same may hold good for gate motors.

The main brakes should be attached to an extension of the motor

shafts. They are usually spring loaded and released by shunt-wound solenoids, there being also hand-releasing gear in case of failure of supply. Emergency brakes are fitted in addition, and these should be located upon a moving part as closely associated with the motor shaft as possible.

Control will be nearly always effected from a remote point, but may be performed either by the drum or the contactor type of equipment. In one A.C.[1] example, viz. the Second Narrows Bridge, Vancouver, the main motors are accelerated by four double-pole contactors of the usual type, which are switched in by separate contacts in the master controller, no relays being employed. It is during the stopping process that the serious danger occurs, and the usual plan is for the motor to be cut off and the brake applied by automatic means at a definite point just before the end of the travel has been reached, the lead being, say, seven degrees. The operator then closes a further contact, which permits the motor to complete the movement at creeping speed.

Whatever the type of control gear, a complete system of interlocks and signal lamps is essential. There are naturally a large number of functions to be fulfilled by the former components, which consist of a set of limit switches operated by rotary drums geared to the respective motor shafts. These are not only designed to bring about the safety stop and slow seating that have already been described, but they must prevent the various motors from functioning in any but the correct order. For example, the main motor must not be permitted to move until the gates are closed and the locks withdrawn, and locking must be impossible until the span has fully seated.

The signal lamps would be located on a desk-board at the control station where they are at all times in full view of the operator. Two colours are advantageous, enabling it to be seen instantly whether the operation is in an intermediate stage or an unsafe condition, usually indicated by the use of red lamps ; or whether the movement is complete and the condition safe, shown by white lamps. Separate lamps should be employed to indicate when the nearly closed as well as the fully closed positions have been reached, and here again a third colour, such as green, is an advantage.[2]

¶ ENGINE CONDITIONING PLANTS.—The last stage in the manufacture of motor-car and other small-cylindered engines consists of the operation usually known as 'running-in', or 'conditioning'. At one time this was carried out by belting the engines as they came from the erection department to line shafting and rotating them for a given time, or until the stiffness had decreased to a certain point. They were then coupled to dynamometers or some other type of mechanical load, and started up, continuing to run in this way until the friction had been further reduced, and the specified output in horse-power was registered.

Nowadays a great saving in time, cost, and convenience is effected by

[1] See *The Engineer*, Oct. 29, 1926, p. 480.
[2] See Johnston, *The Electric Journal*, June 1926, p. 385.

carrying out these two operations by means of the one automatic electrical apparatus. A dynamo and control gear are mounted together to form a self-contained and compact equipment, capable of dealing expeditiously with one engine after another in quick succession. Economy in space as well as time is of importance in a modern automobile factory, the output from which may reach very many times the figures of a few years ago; as may be realized when it is mentioned that one factory in Coventry alone employs no less than fifty-six of these testing sets in constant use, and is about to add to the number.

The principle of the set is to employ the dynamo first as a motor, rotating the engine at increasing speeds, until the power consumption falls to a specified figure, indicating that the friction has been reduced to a given point. Fuel is then supplied to the engine, which is now made to drive the dynamo as a generator, the power developed being either absorbed in resistance grids or fed back into the line. This process is continued until the output rises to a second specified value, showing that the running-in process is completed.

In such an equipment as this a great deal naturally depends on the control gear. Since the testers are almost unskilled in electrical matters, the control must be of the simplest description, consisting of the pressing of two or three push-buttons and the adjustment of a rheostat. The indicating instruments must also be simple and few, such as several signal lamps and two or at most three meters. These requirements, as well as the need for compactness, robustness, and reliability, are supplied by several types of apparatus; and the Heenan-Highfield scheme will be described as a typical case.

In this the electrical gear is all enclosed in a sheet steel enclosure resembling a small kiosk, at one end of which are fixed the bearers upon which the engine under test may be rapidly clamped. The dynamo is conveniently situated just inside the end of the kiosk and is quickly connected by means of a flexible coupling. Above it are the grids, and in front of these a wattmeter calibrated in horse-power, a tachometer, three push-buttons, five indicating lamps, and a field regulator handle. At the back end of the kiosk is a shallow cubicle containing the contactor gear, consisting of a line contactor mechanically interlocked with a second contactor for connecting the armature to the grids (it being possible to close only one of these units at a time), a time-element accelerating unit, and a number of relays mostly operating the signal lamps.

To start operations, the line-contactor is closed by means of the 'start' push-button, connecting the armature to the line in series with all the controlling resistance, and also including the series field of the dynamo. The latter then runs as a compound motor, gradually increasing in speed from say 300 to 900 r.p.m., a minimum relay operating and lighting a signal lamp when this stage has gone far enough. A tester then presses the second button, which sets in motion the time-element unit, cutting out the resistance and the series field. A uniform speed of say 1,100 r.p.m. is the result, during which the current again falls and ultimately operates the minimum relay and its lamp once more.

The engine is now ready for generating, and its carburettor and ignition gear are added and tuned up. By pressing the third push-switch right home, the line-contactor is opened and the grid unit closed, and the engine now generates current into an appropriate portion of the resistance. During this stage coal gas is usually supplied as the fuel, and final adjustments are made to the valves, &c., after which the set is stopped and changed over to petrol.

Again the outfit is motored to full speed by means of the first two push-buttons. The throttle is then opened and the field regulator adjusted to cause the machine to generate into the line at the required rate, operating a relay as the current reverses which causes the ' generating ' lamp to light up in place of the ' motoring '. Finally, a maximum relay operates after the output has reached the specified value, and lights up the last lamp, indicating that the generating stage is finished and the engine can be passed out.

¶ ORGAN BLOWING.—The blowing of organs is frequently carried out electrically, and there is undoubtedly an extensive field for the further application of comparatively small electric motors to replace the inconvenient and relatively costly hand and hydraulic operation that is still the vogue in the majority of cases. Apart from the actual starting of the motor, the control needs to be automatic ; but as centrifugal blowers are generally employed for the larger organs, the regulation is effected non-electrically by means of butterfly throttle valves in the delivery and suction passages of the blower itself. These are connected mechanically with the bellows (forming the reservoir) in such a way that the valves are closed when the former are full, and fully open when the top bellows board has fallen to about the half-way mark. Such a scheme is simple and reliable, but suffers from two defects : there is a considerable wastage of power, since the motor is rotating at full speed the whole time and is always loaded to a certain extent ; and the excess power so absorbed churns and therefore heats the wind when the throttles are closed, sharpening the pitch of the organ appreciably at such times.

For these two reasons reciprocating blowers are preferred by some musicians, in which the motor operates the usual ' feeders ' as used with hydraulic or manual blowing. When either of the latter systems are to be replaced, a reciprocating method is the simplest, cheapest, and most direct. A short discussion of the problem will therefore be of interest.

An organ nearly always requires a wind supply at more than one pressure. For example, a two-manual instrument might be provided with two reservoirs, storing wind at 4 and 2 inches (of water) pressure respectively ; or in the case of a larger model, pressures of 8, 4, and 2 inches might be employed. An organ of small or moderate size, such as a three-manual 50-stop instrument blown by a 3 H.P. motor, would have the one blowing equipment delivering at the highest pressure, and the bellows for the lower pressures would be supplied from the main reservoir through reducing valves. Large organs would, however,

possess a separate blower for each pressure, an example being the four-manual instrument in the Auckland Town Hall, which has three rotary blowers each operated by a 4 H.P. motor.

The accompanying illustration, Fig. 216, will indicate a usual method of working the feeders from a rotary crank shaft. It is important that the speed of the crank be not in excess of 30 revs. per min., otherwise

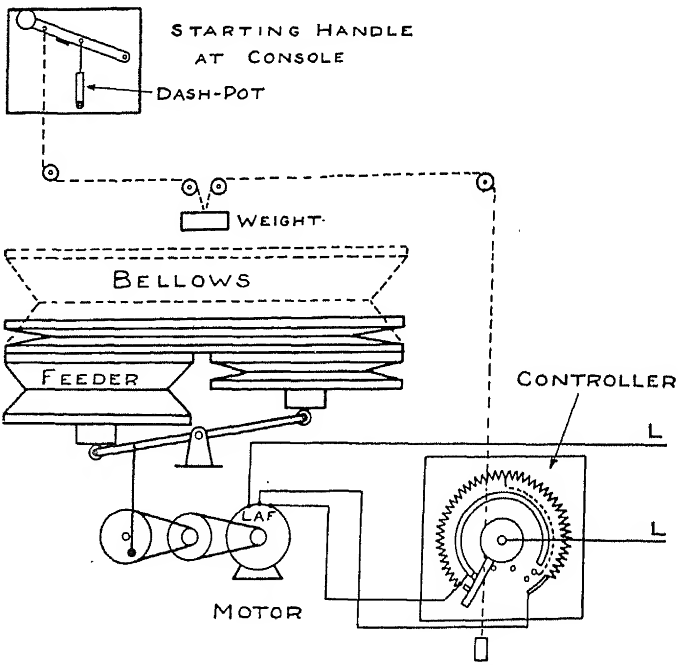



*Fig.* 216. Starter-controller for organ-blowing motor, showing feeders and bellows.

a troublesome pulsation is apt to be transmitted to the wind. Double reduction will be needed between motor and crank, and for this purpose either the 'silent' chain or multiple V-belting are in the opinion of the author the most satisfactory. Their advantages are compactness and silence, both of which enable the gear to be located under the existing feeders. It should be noted that noisy operation is one of the defects of the usual rotary blower, and the expense of a separate and remote blowing chamber is thereby entailed. The reciprocating operating and control gear should, on the other hand, be actually more quiet than the feeders themselves.

With regard to the control gear the usual plan is to provide a separate starter at the keyboards, and a controller near the motor, the latter rheostat being actuated by the top of the bellows, stopping the motor

when they are full, and developing full speed when they are half-empty. The diagram, however, shows a scheme got out by the author for enabling an automatic start to be effected, and full control to be afforded by the one rheostat.

The controller in this case is of much the usual form, with a large number of contacts to lessen the voltage broken on each, and with a high total resistance, sufficient to stall the motor when 'all-in'. The shunt field is connected as with starters; but as the series resistance is now much greater than in the ordinary pattern, a circular contact strip and moving contact are provided to short-circuit this as it is cut out of the armature circuit. If desired, the resistance so dealt with can be cut into the field circuit in any number of steps (two are shown in the figure) when full speed has been reached, for occasional special demands on the wind supply.

It will be observed that this controller is operated by a cord and small weight wrapped round its pulley, the cord not being attached to the top of the bellows in the usual manner, but being fastened to a weight of, say, 2 lb., that rests on the bellows board when the blower is working. The weight may, however, be hauled up by a handle at the keyboards, and this will be seen to move the controller to the off position. Conversely, it may be allowed to fall slowly on to the bellows by releasing the handle, which descends against the retardation of an air dash-pot, automatically starting the motor. When the descending weight meets the rising bellows, the control of the motor passes into the hands of the bellows themselves; but the organist may begin to play the instant after he releases the handle.

A variant of the above method, including a simple water rheostat, has been successfully employed by the author, and is described in a recent [1] paper.

## Conclusion

The foregoing pages will have demonstrated to what an extent the application of the electric motor in industry has been furthered by far-reaching development in control gear design. Not only has the management of the motor been taken out of the hands of the operator, leaving him free to devote the whole of his attention to the industrial process that is being carried out, but the work is effected at a uniform high speed, and effective protection is accorded to the complete electrical system, to the driven apparatus, to all those concerned in the process, and to the operator himself.

These services are undoubtedly of vital importance to any process or operation, and to industry generally; and the author has endeavoured to describe in detail and collectively the methods and devices whereby the results have been attained. Great as has been the development in the past two decades, progress at the present time is still intense, and further notable advances can be anticipated in the same direction.

[1] See 'The Design of Liquid Rheostats,' *Journal I.E.E.*, vol. 60, February 1922, pp. 209 and 210.

It is possible to forecast the lines along which developments will proceed in the near future. First, the gains that have already been made will be consolidated by standardization of methods. Similar results have been achieved by independent workers and departments, employing different designs ; and of these alternatives the most worthy is being adopted in each case and the others are becoming obsolete. An instance of this was described in connexion with lift practice, in which the contactor methods of standard industrial control are being substituted for the hitherto usual solenoid operation.

Secondly, extended use will be made of the results of research, in the application of pure scientific principles. By this means designs will be endowed with greater reliability and efficiency. Problems in connexion with arc suppression and magnetic operation among others are thus in process of being solved.

Thirdly, control gear in general will become more and more automatic, thereby directly increasing its services to industry. The recent successful automatic operation of large mine hoists is a notable case of this development, which is characteristic of the whole trend of control equipment of to-day.

It can therefore be stated with confidence that the subject of industrial control gear will not cease to be of direct interest both to industry and to engineering science for some considerable time ; and that the principles upon which this control is based will continue to be of the greatest importance to those concerned in its manufacture and utilization.

# APPENDIX

## TABLE 12

## TEMPERATURE SCALES

Conversion of Centigrade Readings to Fahrenheit, and vice versa

| ° C. | ° F. | ° C. | ° F. | ° C. | ° F. | ° C. | ° F. | ° C. | ° F. | ° C. | ° F. |
|---|---|---|---|---|---|---|---|---|---|---|---|
| −10 | 14 | 23 | 73·4 | 56 | 132·8 | 89 | 192·2 | 122 | 251·6 | 200 | 392 |
| −9 | 15·8 | 24 | 75·2 | 57 | 134·6 | 90 | 194 | 123 | 253·4 | 210 | 410 |
| −8 | 17·6 | 25 | 77 | 58 | 136·4 | 91 | 195·8 | 124 | 255·2 | 220 | 428 |
| −7 | 19·4 | 26 | 78·8 | 59 | 138·2 | 92 | 197·6 | 125 | 257 | 230 | 446 |
| −6 | 21·2 | 27 | 80·6 | 60 | 140 | 93 | 199·4 | 126 | 258·8 | 240 | 464 |
| −5 | 23 | 28 | 82·4 | 61 | 141·8 | 94 | 201·2 | 127 | 260·6 | 250 | 482 |
| −4 | 24·8 | 29 | 84·2 | 62 | 143·6 | 95 | 203 | 128 | 262·4 | 300 | 572 |
| −3 | 26·6 | 30 | 86 | 63 | 145·4 | 96 | 204·8 | 129 | 264·2 | 400 | 752 |
| −2 | 28·4 | 31 | 87·8 | 64 | 147·2 | 97 | 206·6 | 130 | 266 | 500 | 932 |
| −1 | 30·2 | 32 | 89·6 | 65 | 149 | 98 | 208·4 | 131 | 267·8 | 600 | 1,112 |
| 0 | 32 | 33 | 91·4 | 66 | 150·8 | 99 | 210·2 | 132 | 269·6 | 700 | 1,292 |
| 1 | 33·8 | 34 | 93·2 | 67 | 152·6 | 100 | 212 | 133 | 271·4 | 800 | 1,472 |
| 2 | 35·6 | 35 | 95 | 68 | 154·4 | 101 | 213·8 | 134 | 273·2 | 900 | 1,652 |
| 3 | 37·4 | 36 | 96·8 | 69 | 156·4 | 102 | 215·6 | 135 | 275 | 1,000 | 1,832 |
| 4 | 39·2 | 37 | 98·6 | 70 | 158 | 103 | 217·4 | 136 | 276·8 | | |
| 5 | 41 | 38 | 100·4 | 71 | 159·8 | 104 | 219·2 | 137 | 278·6 | | |
| 6 | 42·8 | 39 | 102·2 | 72 | 161·6 | 105 | 221 | 138 | 280·4 | | |
| 7 | 44·6 | 40 | 104 | 73 | 163·4 | 106 | 222·8 | 139 | 282·2 | | |
| 8 | 46·4 | 41 | 105·8 | 74 | 165·2 | 107 | 224·6 | 140 | 284 | | |
| 9 | 48·2 | 42 | 107·6 | 75 | 167 | 108 | 226·4 | 141 | 285·8 | | |
| 10 | 50 | 43 | 109·4 | 76 | 168·8 | 109 | 228·2 | 142 | 287·6 | | |
| 11 | 51·8 | 44 | 111·2 | 77 | 170·6 | 110 | 230 | 143 | 289·4 | | |
| 12 | 53·6 | 45 | 113 | 78 | 172·4 | 111 | 231·8 | 144 | 291·2 | | |
| 13 | 55·4 | 46 | 114·8 | 79 | 174·2 | 112 | 233·6 | 145 | 293 | | |
| 14 | 57·2 | 47 | 116·6 | 80 | 176 | 113 | 235·4 | 146 | 294·8 | | |
| 15 | 59 | 48 | 118·4 | 81 | 177·8 | 114 | 237·2 | 147 | 296·6 | | |
| 16 | 60·8 | 49 | 120·2 | 82 | 179·6 | 115 | 239 | 148 | 298·4 | | |
| 17 | 62·6 | 50 | 122 | 83 | 181·4 | 116 | 240·8 | 149 | 300·2 | | |
| 18 | 64·4 | 51 | 123·8 | 84 | 183·2 | 117 | 242·6 | 150 | 302 | | |
| 19 | 66·2 | 52 | 125·6 | 85 | 185 | 118 | 244·4 | 160 | 320 | | |
| 20 | 68 | 53 | 127·4 | 86 | 186·8 | 119 | 246·2 | 170 | 338 | | |
| 21 | 69·8 | 54 | 129·2 | 87 | 188·6 | 120 | 248 | 180 | 356 | | |
| 22 | 71·6 | 55 | 131 | 88 | 190·4 | 121 | 249·8 | 190 | 374 | | |

TABLE 13

B.H.P. REQUIRED FOR MAIN-AND-TAIL AND ROPE HAULAGE SYSTEMS AT TEN MILES AN HOUR

| *Actual Incline in Inches per Yard.* | *Virtual Incline in Inches per Yard.* | *Load in Tons.* | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 5 | 7·5 | 10 | 15 | 20 | 25 | 30 | 35 | 40 | 45 | 50 |
| −2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| −1 | 1 | 8·3 | 12·5 | 16·6 | 25 | 33·2 | 41·4 | 50 | 58 | 66·4 | 75 | 80·8 |
| 0 | 2 | 16·7 | 25 | 33·3 | 50 | 66·6 | 83 | 100 | 116 | 133 | 150 | 166 |
| 1 | 3 | 25 | 37·7 | 50 | 75 | 100 | 125 | 150 | 173 | 200 | 225 | 250 |
| 2 | 4 | 33·4 | 50 | 67·5 | 100 | 134 | 167 | 200 | 233 | 270 | 300 | 334 |
| 3 | 5 | 41·5 | 62 | 83·5 | 125 | 167 | 208 | 250 | 290 | 334 | 375 | 416 |
| 4 | 6 | 50 | 75 | 100 | 150 | 200 | 250 | 300 | 350 | 400 | 450 | 500 |
| 5 | 7 | 58·3 | 87 | 117 | 175 | 234 | 294 | 350 | 408 | 468 | 525 | 588 |
| 6 | 8 | 66·3 | 100 | 133 | 200 | 267 | 333 | 400 | 465 | 532 | 600 | 666 |
| 7 | 9 | 75 | 112 | 150 | 225 | 300 | 375 | 450 | 520 | 600 | 675 | 750 |
| 8 | 10 | 83·5 | 124 | 166 | 250 | 333 | 420 | 500 | 580 | 664 | 750 | 830 |
| 9 | 11 | 91 | 137 | 183 | 275 | 366 | 459 | 550 | 640 | 732 | 825 | 918 |
| 10 | 12 | 99 | 150 | 200 | 300 | 400 | 500 | 600 | 696 | 800 | 900 | 1,000 |
| 11 | 13 | 108 | 162 | 217 | 325 | 433 | 542 | 650 | 755 | 868 | 975 | 1,080 |
| 12 | 14 | 116 | 174 | 230 | 350 | 466 | 584 | 700 | 815 | 932 | 1,050 | 1,168 |

NOTE.—Main rope haulage, or 'rope' haulage, is adopted for operating a single road with a sufficient gradient (i.e. exceeding about 3 in. per yard) to enable the tubs to return to the loading-point by gravity. The tail rope is a necessary addition for slighter gradients.

TABLE 14

B.H.P. REQUIRED FOR ENDLESS ROPE HAULAGE WITH AN EVENLY DISTRIBUTED LOAD ON A ROAD 1,000 YARDS IN LENGTH

| Actual Incline in Inches per Yard. | Virtual Incline in Inches per Yard. | Output in Pounds per Minute. | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 200 | 300 | 400 | 500 | 600 | 700 | 800 | 900 | 1,000 | 1,250 | 1,500 | 1,750 | 2,000 | 2,250 | 2,500 | 2,750 | 3,000 |
| −2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| −1 | 1 | 0·5 | 0·75 | 1 | 1·2 | 1·5 | 1·7 | 2 | 2·3 | 2·5 | 3·1 | 3·7 | 4·4 | 5 | 5·6 | 6·2 | 6·9 | 7·5 |
| 0 | 2 | 1 | 1·5 | 2 | 2·5 | 3 | 3·5 | 4 | 4·6 | 5 | 6·3 | 7·6 | 8·9 | 10 | 11·4 | 12·7 | 14 | 15 |
| 1 | 3 | 1·5 | 2·3 | 3 | 3·8 | 4·6 | 5·3 | 6 | 6·8 | 7·6 | 9·5 | 11·4 | 13·3 | 15·2 | 17 | 19 | 21 | 23 |
| 2 | 4 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 12·6 | 15 | 17·6 | 20 | 23 | 25 | 28 | 30 |
| 3 | 5 | 2·5 | 3·8 | 5 | 6·3 | 7·6 | 8·9 | 10 | 11·4 | 12·7 | 15·8 | 19 | 22·3 | 25·4 | 28 | 32 | 35 | 38 |
| 4 | 6 | 3 | 4·5 | 6 | 7·6 | 9 | 10·6 | 12 | 13·7 | 15·2 | 19 | 22·8 | 26·6 | 30·4 | 34 | 30 | 42 | 45 |
| 5 | 7 | 3·5 | 5·3 | 7 | 8·8 | 10·5 | 12·4 | 14 | 16 | 17·7 | 22 | 26·5 | 31 | 35 | 40 | 44 | 49 | 53 |
| 6 | 8 | 4 | 6 | 8 | 10 | 12 | 14·2 | 16 | 18·2 | 20·4 | 25·3 | 30·4 | 35 | 41 | 45 | 51 | 55 | 60 |
| 7 | 9 | 4·5 | 6·8 | 9 | 11·4 | 13·7 | 16 | 18 | 20·5 | 22·8 | 28·5 | 34 | 40 | 45 | 51 | 57 | 63 | 68 |
| 8 | 10 | 5 | 7·6 | 10 | 12·6 | 15·2 | 17·7 | 20 | 22·5 | 25·3 | 31·7 | 38 | 44 | 51 | 57 | 63 | 69 | 76 |
| 9 | 11 | 5·5 | 8·3 | 11 | 14 | 16·7 | 19·5 | 22 | 25 | 27·8 | 34·7 | 41·7 | 49 | 55 | 62 | 69 | 76 | 83 |
| 10 | 12 | 6 | 9 | 12 | 15·2 | 18·2 | 21·3 | 24 | 27·3 | 30 | 38 | 45 | 53 | 61 | 68 | 76 | 83 | 90 |
| 11 | 13 | 6·5 | 9·8 | 13 | 16·4 | 19·8 | 23 | 26 | 29·6 | 33 | 41 | 49 | 57 | 66 | 74 | 82 | 90 | 98 |
| 12 | 14 | 7 | 10·8 | 14 | 17·7 | 21·3 | 24·8 | 28 | 31·8 | 35·4 | 44 | 53 | 62 | 71 | 80 | 88 | 97 | 106 |

NOTE.—Endless rope haulage is used whenever two rail tracks can be laid.

## POWER REQUIRED FOR VARIOUS INDUSTRIAL OPERATIONS

NOTE.—The following tables, Nos. 15 to 24, are intended to afford an approximate guide as to the size of motor required for operating various classes of machinery. In using the tables it should be remembered that exact information on this head can in many cases be supplied only when full details as to working conditions have been supplied. This is especially so with regard to the particulars in Tables 15, 16, and 17; for the power required by machine tools varies quite considerably according to shop practice and the nature of the product. For example, the work performed by cutting tools has increased very greatly during recent years owing to the substitution of high-speed for carbon steel. Again, a boring-mill that is employed in skimming commutators will demand very much less power than one used for machining heavy castings; and so on.

The size of motor specified for individual machines is in every case that required for driving that machine at its greatest output independently of others. When a horse-power is being fixed for group drive, however, advantage may be taken of the fact that any particular machine in an engineering shop is only working at an average of about 30 per cent. full load, and the size of the motor reduced accordingly. Examples of group drive from actual modern practice are given in Table 17.

### TABLE 15

### POWER REQUIRED FOR ENGINEERING MACHINE TOOLS

PORTABLE DRILLS

| *Drilling Capacity in Steel. Inches.* | *B.H.P.* |
|---|---|
| ½ | 0·5 |
| 2 | 2·5 |

VERTICAL AND SENSITIVE DRILLERS

| *Diam. of Spindle. Inches.* | *B.H.P.* |
|---|---|
| 1 | 2 |
| 1¼ | 3 |
| 1½ | 4 |
| 1¾ | 5 |
| 2 | 7·5 |
| 2½ | 10 |
| 3 | 12·5 |

NOTE.—For ordinary drilling the above motor sizes can be reduced by about 50 per cent.

RADIAL DRILLERS

| *Length of Arm. Feet.* | *B.H.P.* |
|---|---|
| 3 | 5 |
| 4 | 7·5 |
| 5 to 6 | 10 |
| 6 to 10 | 15 |

VERTICAL BORING-MILLS

| *Diam. of Table. Feet.* | *B.H.P.* |
|---|---|
| 4 | 5 |
| 6 | 10 |
| 9 | 15 |
| 12 | 20 |
| 14 | 25 |
| 16 | 30 |

### Screw-cutting Lathes

| Height of Centres. Inches. | B.H.P. |
|---|---|
| 6 | ½ to 1 |
| 12 | 1 „ 2 |
| 24 | 3 „ 5 |

### Engine Lathes

| Swing Diam. Feet. | B.H.P. |
|---|---|
| 2 | 7·5 to 10 |
| 4 | 15 „ 20 |
| 6 | 20 „ 30 |
| 8 | 25 „ 35 |
| 14 | 35 „ 50 |

### Turret Lathes

| Bar Diam. Inches. | B.H.P. |
|---|---|
| ⅝ | 1 |
| 1 | 1·5 |
| 1½ | 3 |
| 2 | 5 |
| 3 | 7·5 |
| 3½ | 10 |

### Automatic Turning Lathes

| Swing Diam. Inches. | B.H.P. |
|---|---|
| 8 | 7 |
| 19 | 7 |
| 23 | 10 |

### Automatic Screw-cutting Lathes

| Bar Diam. Inches. | B.H.P. |
|---|---|
| 1 | 3·5 |
| 1½ | 6 |
| 2 | 7 |
| 3 | 8 |

### Wheel Lathes

| Swing Diam. Inches. | B.H.P. |
|---|---|
| 48 | 25 |
| 50 | 35 |
| 55 | 50 |

### Small Millers

| Travel. Inches. | B.H.P. |
|---|---|
| 5 | 2·5 |
| 8 | 3 |
| 10 | 5 |
| 12 | 7·5 |

### Large Multi-spindle Millers

| Width between Housings. Feet. | B.H.P. |
|---|---|
| 2 | 7·5 to 25 |
| 3 | 10 ,, 35 |
| 4 | 15 ,, 50 |
| 5 | 20 ,, 65 |

### Bench and Portable Grinders

| Wheel Dimensions. Inches. | Speed—R.P.M. | B.H.P. |
|---|---|---|
| $4\frac{1}{2} \times \frac{3}{8}$ | 4,200 | 0·25 |
| $8 \times \frac{3}{4}$ | 2,600 | 0·5 |
| $10 \times 1$ | 2,050 | 1 |
| $12 \times 1\frac{1}{2}$ | 1,700 | 2 |
| $14 \times 2$ | 1,600 | 3 |

### Plain and Universal Grinders

| Wheel Dimensions. Inches. | B.H.P. |
|---|---|
| $8 \times \frac{1}{2}$ | 2 |
| $10 \times \frac{3}{4}$ | 3 |
| $12 \times 1$ | 5 |
| $14 \times 1\frac{1}{4}$ | 6 |
| $16 \times 1\frac{1}{2}$ | 10 |
| $20 \times 2$ | 15 |

### Standard Planers

| Width of Bed. Feet. | B.H.P. |
|---|---|
| 2 | 5 |
| 3 | 10 |
| 4 | 25 |
| 5 | 30 |
| 6 | 35 |
| 7 | 45 |
| 10 | 60 |
| 16 | 75 |

### Plate-edge Planers

| Plate Thickness. Inches. | B.H.P. |
|---|---|
| 1 | 10 |
| $1\frac{1}{2}$ | 15 |
| 2 | 20 |

### Shapers

| Length of Stroke. Inches. | B.H.P. |
|---|---|
| 18 | 2 |
| 22 | 5 |
| 26 | 7·5 |

### Slotters

| *Length of Stroke. Inches.* | *B.H.P.* |
|---|---|
| 6 | 2 |
| 10 | 4 |
| 12 | 5 |
| 15 | 7·5 |
| 18 | 10 |
| 24 | 12·5 |
| 30 | 15 |
| 36 | 20 |

### Punching and Shearing Machines

| *Punching Capacity. Inches.* | *Shearing Capacity. Inches.* | *B.H.P.* |
|---|---|---|
| $\frac{5}{8} \times \frac{5}{8}$ | $3 \times \frac{5}{8}$ | 3 |
| $\frac{3}{4} \times \frac{3}{4}$ | $4 \times \frac{3}{4}$ | 3·5 |
| $\frac{7}{8} \times \frac{7}{8}$ | $5 \times \frac{7}{8}$ | 4 |
| $1 \times 1$ | $6 \times 1$ | 5 |
| $1\frac{1}{2} \times 1$ | $8 \times 1$ | 7·5 |
| $2\frac{1}{4} \times 1\frac{1}{4}$ | $8 \times 1\frac{1}{4}$ | 10 |
| $2\frac{1}{2} \times 1\frac{1}{2}$ | $8 \times 1\frac{1}{2}$ | 15 |
| $3\frac{1}{2} \times 2$ | $10 \times 2$ | 20 |

### Drop Hammers (Friction)

| *Weight of Tup. Cwt.* | *Speed of Lift. Feet per Min.* | *B.H.P.* |
|---|---|---|
| 3 | 450 | 7·5 |
| 10 | 400 | 25 |
| 20 | 400 | 45 |
| 40 | 350 | 80 |
| 60 | 300 | 125 |
| 100 | 300 | 200 |

### Overhead Cranes

| *Capacity. Tons.* | *Hoist.* | *B.H.P. Trolley.* | *Bridge.* |
|---|---|---|---|
| 3 | 7·5 | 1 | 7·5 |
| 7·5 | 12·5 | 2 | 12·5 |
| 15 | 15 | 3 | 15 |
| 50 | 35 | 12·5 | 25 |

## Table 16

## POWER REQUIRED FOR SHIPYARD TOOLS

### Plate Bending Rolls

| *Plate Width. Feet.* | *B.H.P.* |
|---|---|
| 6 | 6 |
| 12 | 15 |
| 16 | 25 |
| 20 | 35 |
| 24 | 50 |

PLATE STRAIGHTENING ROLLS

| *Plate Width. Feet.* | *B.H.P.* |
|---|---|
| 5 | 7·5 |
| 6 | 10 |
| 7 | 20 |
| 10 | 35 |

ARMOUR PLATE SAWING MACHINE

| *Plate Thickness. Inches.* | *B.H.P.* |
|---|---|
| 12 | 40 |
| 20 | 50 |

| | *B.H.P.* |
|---|---|
| Triple Punching, Shearing and Manhole Punching Machine, for $1\frac{1}{2}$ inch holes in $1\frac{1}{2}$ inch plates, and 22 inch manholes in $\frac{5}{8}$ inch plates | 20 |
| Armour Plate End Miller | 40 |
| Armour Plate Breast Planer (Single) | |
| Main drive | 50 |
| Cross traversing | 15 |
| Swivelling | 7·5 |
| Bar traversing | 4 |
| Armour Plate Grinder, 36 inch wheel | |
| Main drive | 40 |
| Feeding and traversing | 10 |
| Head elevating | 3 |

## TABLE 17

## POWER REQUIRED FOR GROUP DRIVING OF MACHINE TOOLS

The following are examples of group drive from actual practice, in which the horse-power is known to be sufficient for the purpose and not greatly in excess of requirements.

| *No. of Machines.* | *Class of Work.* | *Description of Machines.* | *B.H.P. of Motor.* |
|---|---|---|---|
| 12 | Switchgear Components | Small capstan lathes, 4 in. to 6 in. centres | 15 |
| 10 | ,, ,, | Four-spindle sensitive drillers | 12·5 |
| 16 | ,, ,, | Three-spindle sensitive drillers | 12·5 |
| 11 | Metal Grinding and Polishing | Four 24 in. double-disk grinders and seven 9 in. double-headed cloth polishing bobs | 25 |
| 9 | ,, ,, | 9 in. double-headed cloth polishing bobs | 15 |
| 4 | Plating | Revolving anode plating vats | 3·5 |
| 2 | Woodworking | 18 in. circular saw and 18 in. pendulum saw | 10 |
| 2 | ,, ,, | 18 in. circular saw and 12 in. wedge-cutting saw | 10 |
| 2 | Pattern-making | 6 ft. and 3 ft. wood-turning lathes | 8 |
| 2 | ,, ,, | Three-spindle driller and grinder for planer blades | 6 |
| 17 | Heavy Electrical Engineering | 16 lathes, $8\frac{1}{2}$ to $15\frac{1}{2}$ in. centres; and one 48 in. face plate lathe | 30 |

| No. of Machines. | Class of Work. | Description of Machines. | B.H.P. of Motors. |
|---|---|---|---|
| 11 | Heavy Electrical Engineering | 7 vertical boring-mills, 2 ft. 3 in. to 6 ft. diam. tables; 3 lathes, 11 in. centres; and one 8 in. slotter . | 30 |
| 11 | ,, ,, | 3 horizontal boring machines, 2½ to 5 in. bars; three 24 in. double-headed shapers; 2 slotting machines, 8 in. and 16 in.; one 4 ft. radial driller; and two 5 ft. (wide) planers . | 30 |
| 9 | ,, ,, | Eight 4 ft. boring-mills and one 24 in. double-headed shaper . . | 30 |
| 9 | ,, ,, | 8 lathes, 8½ to 12½ in. centres, and 1 sensitive driller . . . | 15 |
| 3 | ,, ,, | 6 ft. radial drillers . . . | 15 |
| 4 | ,, ,, | 4 ft. radial driller, 12 in. shaper, 8 in. and 24 in. slotters . . . | 15 |
| 15 | ,, ,, | 12 horizontal millers, 12 ×36 in., and three 3-spindle sensitive drillers . | 15 |
| 16 | ,, ,, | 12 capstan lathes, 5½ in. to 11 in. centres; 1 vertical miller; 1 thread miller; 1 key-seating machine; and 1 broach . . . . | 16·5 |
| 24 | ,, ,, | 12 capstan lathes, 5½ in. to 11 in. centres; three 14 in. lathes; three 10 in. shaft grinders; one 4 ft. radial drill; 1 key-seating machine; two 28 in. vertical boring-mills; and 2 pillar drillers . | 16·5 |

## Table 18

## POWER REQUIRED FOR WOODWORKING MACHINERY

### Ordinary Circular Saws

| Diameter. Inches. | B.H.P. |
|---|---|
| 12 | 3 |
| 20 | 5 |
| 26 | 10 |
| 32 | 12·5 |
| 38 | 15 |
| 48 to 60 | 25 to 50 |

### Pendulum Saws

| Diameter. Inches. | B.H.P. |
|---|---|
| 24 | 4 |
| 32 | 5 |

### Band Saws (Ordinary Duty)

| Wheel Diam. Inches. | B.H.P. |
|---|---|
| 24 | 2 |
| 30 | 3 |
| 36 | 4 |

### Band Saws (For Sawing Logs)

| *Log Diam. Feet.* | *B.H.P.* |
|---|---|
| 2 to 3 | 30 to 50 |
| 5 ,, 6 | 60 ,, 80 |

### Wood-turning Lathes

| *Height of Centres. Inches.* | *B.H.P.* |
|---|---|
| 6 | 2 |
| 8 | 2 |
| 12 | 3 |
| 15 | 4 |

### Planing Machines

| *Width of Work. Inches.* | *B.H.P.* |
|---|---|
| 22 | 10 |
| 30 | 20 |

### Surface Planing Machines

| *Width of Work. Inches.* | *B.H.P.* |
|---|---|
| 12 | 3 |
| 16 | 4 |
| 22 | 5 |

### Moulding Machines (For work up to 6 in. deep)

| *No. of Spindles.* | *B.H.P.* |
|---|---|
| Single | 3 |
| Double | 5 |

### Double Disk Grinders

| *Diam. of Disk. Inches.* | *B.H.P.* |
|---|---|
| 22 | 4 |
| 30 | 5 |
| 36 | 6 |

### Miscellaneous

| *Machine.* | *B.H.P.* |
|---|---|
| Mortising Machines (Chain and Chisel), for work 12 in. × 8 in. | 4 |
| Tenoning Machine, for work 24 in. × 6 in. | 7·5 |
| Recessing and Stair-stringing Machine | 2 |
| Vertical Boring Machine ($1\frac{1}{2}$ in. bit) | 2 |

TABLE 19

# POWER REQUIRED FOR PRINTING MACHINERY

## LETTERPRESS AND LITHOGRAPHIC PRINTING MACHINERY

| *Type of Machine.* | *Impressions per Hour.* | *B.H.P.* |
|---|---|---|
| Furnival Quad Demy | 1,600 | 5 |
| Konig & Bauer Letterpress | 1,240 | 3 |
| Double Demy Fieldhouse | 1,500 | 2 |
| Double Royal Two Colour Payne | 1,400 | 3 |
| Demy Furnival Litho | 900 | 2 |
| Large Alumer Press | 1,100 | 4 |
| Five Bronzing Machines | — | 5 |
| Wharfedale Cutter | 6,000 | 3 |
| Baron Tube Machine | 4,500 | 3 |
| Martin Folder | 1,200 | 2 |
| 40 in. Guillotine | — | 3 |
| Six Crease-pressing Machines | — | 9 |

## NEWSPAPER PRINTING MACHINERY

| *Type of Machine.* | *Impressions per Hour.* | *B.H.P.* |
|---|---|---|
| One 4-page Hoe Machine | 24,000 | 20 |
| ,, 8-page ,, | 24,000 | 35 |
| ,, 16-page ,, | 24,000 | 60 |
| ,, 32-page ,, | 24,000 | 120 |
| ,, 10-page Webb Perfecting Press | 12,000 | 15 |
| ,, 10-page ,, ,, | 24,000 | 30 |
| ,, 12-page ,, ,, | 12,000 | 20 |
| ,, 12-page ,, ,, | 24,000 | 30 |
| ,, 32-page ,, ,, | 12,000 | 30 |

## GENERAL PRINTING MACHINERY

| *Type of Machine.* | *Impressions per Hour.* | *B.H.P.* |
|---|---|---|
| Demy | 1,500 | $\frac{3}{4}$ |
| Double Crown | 1,350 | $1\frac{1}{4}$ |
| Double Demy | 1,300 | $1\frac{1}{2}$ |
| Double Royal | 1,300 | 2 |
| Quad Crown | 1,250 | 3 |
| Quad Demy | 1,200 | 3 to $3\frac{1}{2}$ |
| Quad Royal | 1,200 | $3\frac{1}{2}$ ,, 4 |
| D.D. Folder | — | $\frac{1}{2}$ |
| Q.C. and D.D. Folder | — | 1 |
| Round Cornering | — | $\frac{1}{2}$ |
| Punching and Eyeletting | — | $\frac{1}{4}$ |
| Bronzing and Dusting | — | $\frac{1}{4}$ to $\frac{1}{2}$ |
| Envelope and Label Punching | — | 1 ,, 2 |
| Cropper Platen | — | $\frac{1}{2}$ |
| Guillotine Self-Clamping— | | |
| 26 in. | — | 1 |
| 36 in. | — | 2 |
| 42 in. | — | 3 |
| 48 in. | — | 4 |
| Furnival Centre Driven High Speed Machines— | | |
| Double Demy | — | 3 |
| Quad Crown | — | $3\frac{1}{2}$ |
| Quad Demy | — | $3\frac{1}{2}$ |

## TABLE 20

### POWER REQUIRED FOR CALICO PRINTING, BLEACHING, DYEING, AND FINISHING MACHINERY

| *Type of Machine.* | *B.H.P.* |
|---|---|
| 29-cylinder horizontal drying machine, size 8 ft. 6 in. | 10 |
| 29-cylinder horizontal drying machine, with mangle 5 ft. 6 in. wide | 15 to 20 |
| 23-cylinder vertical drying machine, with 4 sizing vats | 15 |
| 20-ft. Stretcher Stenter | 5 to $7\frac{1}{2}$ |
| 90-ft. Stenter | 20 ,, 25 |
| Stenter Fan | 20 ,, 25 |
| Stenter Jig | 5 |
| 2-Bowl Schreiner Calender, 5 ft. face | 20 to 25 |
| 10-colour Printing Machine | 40 ,, 45 |
| 12- ,, ,, | 45 ,, 50 |
| Scouring Range | 15 ,, 20 |
| 72-in. Hydro Extractor | 10 ,, 15 |
| 36-in. ,, ,, | 5 ,, $7\frac{1}{2}$ |

## TABLE 21

### POWER REQUIRED FOR COTTON-MILL MACHINERY

| *Type of Machine.* | *B.H.P.* |
|---|---|
| Willow | 4 |
| Buckley Opener | 5 to 10 |
| Crighton Single Opener | 6 |
| ,, Double ,, | 12 |
| Single Scutcher | 5 |
| Double ,, | 10 |
| 45-in. Flat Card | $\frac{3}{4}$ to 1 |
| Drawing Frames | $7\frac{1}{2}$ deliveries per horse-power |
| Ring Spinning Frames | 75/100 spindles per horse-power |
| Mule Spinning | 80/110 ,, ,, ,, |
| Ring Doubling, dry | 35/75 ,, ,, ,, |
| ,, ,, wet | 30/70 ,, ,, ,, |
| Slasher Sizer | 5 |
| Plain Looms 36/40 in. | $\frac{1}{4}$ to $\frac{1}{3}$ |
| ,, 40/60 in. | $\frac{1}{3}$ ,, $\frac{5}{8}$ |
| ,, 60/80 in. | $\frac{5}{8}$ ,, $\frac{3}{4}$ |
| ,, 104 in. | $\frac{7}{8}$ ,, 1 |
| ,, 124 in. | 1 ,, $1\frac{1}{4}$ |
| Extra for Jacquard | $\frac{1}{3}$ |
| Quick Traverse Winders | 80 drums per horse-power |
| Ordinary Winding Frame | 300 spindles per horse-power |
| Plaiting Machine | $\frac{1}{2}$ |
| Bundling Press | $\frac{1}{2}$ to 1 |
| Size Vats | 2 ,, 4 |

## Table 22

### POWER REQUIRED FOR WOOLLEN AND WORSTED MACHINERY

| *Type of Machine.* | *B.H.P.* |
|---|---|
| 360-Spindle Worsted Mule | 10 |
| 40-Spindle Pirn Winder | 5 |
| Cheese Winder, 40 drums | 2½ |
| Warping Machine | 1½ |
| Soaping ,, | 2 |
| Scouring ,, | 7½ |
| Milling ,, | 10 to 20 |
| Hot Air Stenter | 10 ,, 20 |
| Cloth Cutting Machine | 2 ,, 5 |
| Raising Machine | 10 |
| Brushing ,, | 7½ |
| Condenser Card and Scribbler | 10 to 12½ |
| Willow | 15 |
| Back Washing Machine | 5 |
| French Drawing Range | 20 to 25 |
| Gill Boxes | 1 ,, 3 |
| Petrie Dryer | 10 ,, 15 |
| Fly Frame | 30/40 spindles per horse-power |
| Ring Doubler | 40/50 ,, ,, |
| Cap Frame | 30/40 ,, ,, |
| Devil | 6 to 8 |

## Table 23

### POWER REQUIRED FOR MISCELLANEOUS MACHINERY

| | *B.H.P.* |
|---|---|
| Ash Hoist | 2 |
| Boot Polishing Machines | ½ to 2 |
| Cake and Whisking Machine | ⅛ ,, 2 |
| Capstan, 15 tons, 25 ft. per minute | 35 |
| Coffee Roasting Machine | 1½ to 2 |
| Combined Blending and Sifting Machine | 2 ,, 3 |
| Dough Kneading Machines— | |
| ½ sack | 1 ,, 1½ |
| 1 ,, | 1½ ,, 2 |
| 1½ ,, | 3 |
| 2 ,, | 4 |
| 3 ,, | 5 to 6 |
| 4 ,, | 6 ,, 7 |
| Goods Hoist— | |
| Worked by gearing, 10 cwt., 60 ft. per minute | 4 ,, 5 |
| Horizontal Stone Saw, to take 8 in. Blades | 15 |
| Jewellers' Plant | ⅛ to 3 |
| Organ Blowing (up to 40 stops) | 1 ,, 2 |
| Plate Glass Polishing Machine | 1½ ,, 2 |
| Sack Cleaner | 1 ,, 1½ |
| Saddlers' Sewing Machines | ½ ,, 1 |
| Sausage Machine | ½ ,, 1 |
| Sewing Machine | $\frac{1}{10}$ ,, ⅛ |
| Stone Shapers and Planers, 6 in.×4 in.×4 in. | 5 |
| Tobacco Cutting Machine, 6 Blade | ½ to 1 |
| Ventilating Fans, 12 in. to 36 in. | ¼ ,, 1 |

### Bookbinding and Box-making Plant

| | *Size.* | *B.H.P.* |
|---|---|---|
| Box Corner Cutting Machine . . | — | 3 to 5 |
| Combined Scoring, Bending, and Grooving Machine | 30 in. × 50 in. between side gauges | 3 „ 5 |
| Board Scoring Machine . . . . | 14 in. | ½ „ 2 |
| „ „ . . . | 26 in. | 1 „ 3 |
| „ „ . . . | 42 in. | 2 „ 5 |

### Carpet-beating Plant

| | |
|---|---|
| Beater taking Carpet 6 yards wide . . . . | 6 |
| Tumbler Carpet Beater to beat 120 square yards . | 6 |

## Table 24

## POWER REQUIRED FOR ROLLING MILLS

It is naturally not a very easy matter to prescribe the power requirements of a load with so many variables as a rolling mill. Certain examples have been quoted in the text, which may be considered as typical of the most modern practice, including both main rolls and auxiliaries. Further data are given below.

1. Slabbing and Cogging Mills.
   The power demand (peak value) ranges up to 18,000 H.P. with rolls of 48 in. in diameter.
2. Universal Plate Mills.
   The power demand (peak value) ranges up to 18,000 H.P. for rolls of 34 in. diameter.
3. Ordinary Plate Mills.
   For two-high reversing mills the power demand (peak value) is up to 12,000 H.P.
   For three-high (continuous running) mills, the peak value is up to 3,000 H.P. when a fly-wheel is employed.
4. Sheet and Tinplate Mills (non-reversing).
   Power demand per stand is about 300 H.P. There are usually 4, 6, 8, or 12 stands per mill.
5. Rail and Section Mills.
   The power demand (peak value) is up to 10,000 H.P. for rolls of 30 in. diameter.
6. Merchant Mills.
   Power demand as under :

| *Roll Diameter. Inches.* | *Number of Stands.* | *Demand in B.H.P.* | |
|---|---|---|---|
| | | *Simple Mills.* | *Belgian Mills.* |
| 8 | 5 | 250 | 300 |
| 9 | 5 | 275 | 350 |
| 10 | 5 | 300 | 500 |
| 12 | 5 | 350 | 600 |
| 14 | 4 | 500 | 800 |
| 16 | 3 | 800 | — |
| 18 | 3 | 1,200 | — |

## TABLE 25

### FUSING CURRENTS OF VARIOUS WIRES

The following table is of use for two purposes, namely, for ascertaining the limiting current that a given wire will carry without melting, and for prescribing the size of fuse-wire for rupturing a circuit upon the current rising to a given value.

Note that the figures are for bare wires of such a length (averaging about 6 in.) that the cooling effect of the terminals is negligible. When the wires are enclosed in the usual porcelain holder fitted with asbestos tube, the fusing current with the holder hot (i.e. heated by the continued passage of the normal current) is 0·85 to 0·9 times the values in the table.

The figures have been compiled by means of Preece's formula, which has already been quoted and employed on p. 102. It states that the fusing current $I = ad^{\frac{3}{2}}$, where $d$ is the diameter of the wire in inches, and $a$ is a constant having the following values for various metals :

| | | | |
|---|---|---|---|
| Copper | 10,244 | Platinoid | 4,750 |
| Aluminium | 7,585 | Iron | 3,148 |
| Nickel-copper (60 : 40) | 5,680 | Tin | 1,642 |
| Nickel silver | 5,230 | Lead | 1,379 |
| Platinum | 5,172 | Lead-tin (2 : 1) | 1,318 |

Actual fusing currents of the three most useful metals—copper, lead, and tin—are given below.

| *S.W.G.* | *Diameter. Inches.* | *Fusing Current in Amperes.* *Copper.* | *Lead.* | *Tin.* |
|---|---|---|---|---|
| 11 | 0·116 | 405 | 54·5 | 65 |
| 12 | 0·104 | 344 | 46·3 | 55 |
| 13 | 0·092 | 286 | 38·5 | 46 |
| 14 | 0·08 | 232 | 31·2 | 37·15 |
| 15 | 0·072 | 198 | 26·6 | 31·75 |
| 16 | 0·064 | 165·8 | 22·32 | 26·58 |
| 17 | 0·056 | 132·5 | 17·84 | 21·25 |
| 18 | 0·048 | 107·7 | 14·5 | 17·27 |
| 19 | 0·040 | 81·5 | 10·95 | 13·07 |
| 20 | 0·036 | 69·97 | 9·41 | 11·22 |
| 21 | 0·032 | 58·6 | 7·88 | 9·40 |
| 22 | 0·028 | 48 | 6·46 | 7·69 |
| 23 | 0·024 | 38·1 | 5·13 | 6·10 |
| 24 | 0·022 | 33·43 | 4·5 | 5·36 |
| 25 | 0·02 | 29 | 3·9 | 4·65 |
| 26 | 0·018 | 24·74 | 3·33 | 3·96 |
| 27 | 0·0164 | 21·5 | 2·89 | 3·45 |
| 28 | 0·0148 | 18·44 | 2·48 | 2·96 |
| 29 | 0·0136 | 15·5 | 2·11 | 2·52 |
| 30 | 0·0124 | 14·15 | 1·9 | 2·27 |
| 31 | 0·0116 | 12·8 | 1·72 | 2·06 |
| 32 | 0·0108 | 11·5 | 1·55 | 1·84 |
| 33 | 0·01 | 10·2 | 1·37 | 1·64 |
| 34 | 0·0092 | 9·04 | 1·21 | 1·44 |
| 35 | 0·0084 | 7·88 | 1·06 | 1·26 |
| 36 | 0·0076 | 6·79 | 0·92 | 1·09 |
| 37 | 0·0068 | 5·74 | 0·77 | 0·92 |
| 38 | 0·0060 | 4·76 | 0·64 | 0·76 |
| 39 | 0·0052 | 3·84 | 0·52 | 0·62 |
| 40 | 0·0048 | 3·41 | 0·46 | 0·55 |

The fusing currents of copper wires from 41 to 50 S.W.G. are respectively 2·99, 2·59, 2·21, 1·85, 1·52, 1·25, 0·917, 0·655, 0·346, and 0·324 amperes.

## Table 26

## ARMATURE RESISTANCE OF D.C. MOTORS, IN OHMS

The following table gives the approximate resistance of the armatures of D.C. motors up to 100 H.P. In using these figures it should be noted that they represent the average resistance of a number of models of the same horse-power running at different speeds; e.g. the resistance for a 5 H.P. 220-volt machine varies from about 0·71 to 0·96 ohms, and for a 12·5 H.P. machine at the same voltage from about 0·34 to 0·41 ohms. At any horse-power, the faster machine has the lower resistance. It should also be remembered that the resistance of the armature is modified by a change in the number of poles, a fact that is responsible for the relatively wide variation in the figures for the 5 H.P. motors, the faster models having two and the slower four poles.

| *Size of Motor B.H.P.* | VOLTAGE *110* | *220* | *440* | *500* | *600* |
|---|---|---|---|---|---|
| ½ | 3 | 12 | 48 | 62 | 89 |
| 1 | 1·3 | 5 | 20 | 26 | 37 |
| 2 | 0·8 | 3 | 12 | 15 | 22 |
| 3 | 0·5 | 2 | 8 | 10 | 15 |
| 4 | 0·3 | 1·3 | 5·2 | 6·7 | 9·7 |
| 5 | 0·2 | 0·8 | 3·2 | 4·1 | 6·0 |
| 7·5 | 0·1 | 0·4 | 1·6 | 2·1 | 3·0 |
| 10 | 0·095 | 0·38 | 1·52 | 2·0 | 2·8 |
| 12·5 | 0·09 | 0·37 | 1·48 | 1·9 | 2·7 |
| 15 | 0·06 | 0·23 | 0·92 | 1·2 | 1·7 |
| 20 | 0·04 | 0·15 | 0·60 | 0·77 | 1·1 |
| 25 | 0·03 | 0·12 | 0·48 | 0·62 | 0·9 |
| 30 | 0·025 | 0·10 | 0·40 | 0·52 | 0·75 |
| 35 | 0·021 | 0·085 | 0·34 | 0·44 | 0·63 |
| 40 | 0·018 | 0·07 | 0·28 | 0·37 | 0·52 |
| 45 | 0·015 | 0·06 | 0·24 | 0·31 | 0·45 |
| 50 | 0·013 | 0·05 | 0·20 | 0·26 | 0·37 |
| 60 | 0·010 | 0·04 | 0·16 | 0·21 | 0·30 |
| 80 | 0·008 | 0·03 | 0·12 | 0·15 | 0·22 |
| 100 | 0·006 | 0·023 | 0·09 | 0·12 | 0·17 |

*Note re A.C. Motors.*

It is unfortunately not possible to tabulate the rotor resistances of slip-ring induction motors, on account of the great variation in the rotor voltage, which need have no fixed relationship to that of the stator.

The resistances and reactances of the stators are given by the curves in Fig. 45, p. 80.

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